GEOLOGICAL AND TOPOGRAPHICAL MAPS

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THEIR INTERPRETATION AND USE

A HANDBOOK FOR THE GEOLOGIST AND CIVIL ENGINEER

BY

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PREFACE

HAVING frequently been asked by my students and others for a text-book dealing with the practical problems which are involved in the interpretation of maps, both geological and topographical, I have endeavoured in the following pages to give such descriptions and instructions as will enable the civil engineer and the student of geology to draw sections of the country depicted upon maps, and to ascertain the depth and thickness of the various strata of which it is built up, and their relations to the surface of the ground and to each other.

The importance of a correct solution of this type of problem to the civil engineer, and to all others engaged in work which involves the making of excavations, need not be enlarged upon, and it is hoped that the present volume will be a help to them and to teachers and students of geology and geography.

It has been thought desirable to include a brief summary of the main structural features of rocks for the benefit of those readers who have been unable to obtain a systematic course of instruction in geology; but it is not intended that this should replace the fuller accounts to be found in the text-books of Physical Geology.

The examples given in the illustrations have been, as far as possible, based upon actual districts in the British Isles, but occasionally it has been necessary to simplify these to some extent for the sake of clearness.

In conclusion, I cannot too warmly express my thanks to Professor P. F. Kendall, under whose guidance I acquired my first knowledge of structural geology, and to whom therefore many of the ideas expressed in the present volume are due.

A. R. D.

BELFAST, *Oct.* 1911.

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GEOLOGICAL AND TOPOGRAPHICAL MAPS

CHAPTER I

INTRODUCTORY

I. Topographical Maps

The maps which are published in the ordinary atlas are, as a rule, too small in scale to be of much use to the geologist or to the civil engineer, since in so limited a space it is impossible to indicate more than the mere outline of the topography, such, for example, as the mountain chains, rivers, railways, and the principal towns, and it is not therefore proposed to treat of them at any length in the present volume. In the absence of maps on a larger scale it may in some cases be necessary to use these small maps, and in all instances where a choice is possible, those which are free from heavy washes of colour should be chosen, since too much colour obscures the *black-and-white* detail.

The first objects of the map-maker should be accuracy and clearness, and these should in no case be sacrificed to artistic effect, or to a desire to include more detail than is warranted by the scale.

In the present chapter it is intended to deal principally with maps on a scale of 1 inch to a mile and upwards, as these are sufficiently open to render it possible to indicate, not only roads, rivers, and buildings, but also much of the minor detail and physical relief of the surface.

Topographical maps are now prepared by the govern-

ments of most civilised countries for military purposes, and they may usually be procured at small cost and with little trouble. Such maps naturally give prominence to those features which are of importance to an army in the field, but as these comprise almost every feature which it is possible to indicate upon a map, they are most excellent for ordinary purposes, including the preparation of geological maps, of which they form the basis.

In measuring the distances between places on a map, it must be borne in mind that it is impossible to represent accurately on a sheet of paper portions of the surface of a sphere, and that, in consequence, the distances given on the map will not accurately correspond with the horizontal distances between corresponding points on the surface of the country, though for all ordinary purposes they will be found to be sufficiently near the truth.

The errors necessarily introduced in reducing the surface of a sphere to a plane, will obviously be greater in the case of a map which represents a large portion of the earth's surface, than in a large-scale map covering but a small area. The amount and nature of the distortion will depend upon the method of reduction or "projection" employed.

The problem involved is primarily the projection of the meridians and parallels, which form a framework to which the topographical details may then be adjusted. When dealing with large areas such, for example, as a hemisphere, the projection employed is usually a perspective projection, while in cases of large-scale surveys of more limited areas, some form of conventional projection is chosen, the choice being determined by the uses to which the maps are to be put.

The representation of hilly country on a flat surface involves the reduction of all distances measured on a slope to their horizontal equivalents, and therefore distances measured along a hilly road, say, by means of an accurate cyclometer, would be greater than the corresponding distances obtained from the map. Thus, if the curved

line in Fig. 1 represents the slope of a road crossing a hill, the distance from A to B would be represented on the map by the shorter horizontal distance A C, and not by the length of the curved line A B.

The methods of representing the relief of the surface, that is to say the hills and valleys, require, perhaps, more study than any other part of a topographical map. On the smaller-scale maps the relief is usually indicated by marking the main lines of hills or mountains by means of shading, or it may be, only by the insertion of figures recording the heights of some of the principal summits, and of certain points along the main roads and railways.

In the case of maps devoid of any such indications of the physical relief, we may of course conclude that the rivers occupy the low ground, while lines drawn to separate

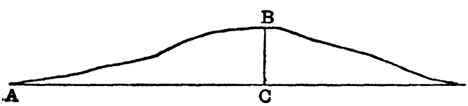


FIG. 1.

the areas drained by the respective rivers and their tributaries, may be taken in most instances as occupying the highest ground.

With larger scales it becomes possible to indicate the surface features with much greater accuracy, and the method chosen must depend upon whether the map is to be used for purposes of accurate measurement, or is designed to give a general idea of the shape of the country at a glance.

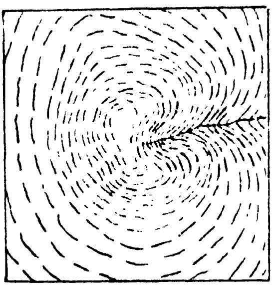
Many very beautiful maps have been produced in which the slope of the ground is indicated by means of shading, consisting of a number of short strokes drawn at right angles to the slope, and indicating, by their thickness and relative proximity, the degree of inclination. In a map shaded in this fashion the steepest slope will always be at right angles to the "*hachure-lines*," and the degree

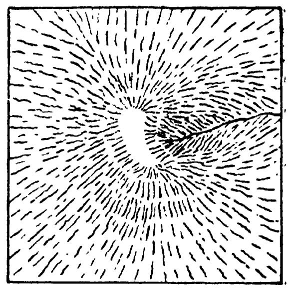
of slope will be indicated by the depth of the shading which they produce.

Another system of shading is by drawing the hachures in the direction of the slope, and in this case also the depth of the shading will be proportional to the angle of the slope.

Examples of the two types of shading just described are given in Figs. 2 and 3.

Hachure lines alone give but little indication of the relative heights of different parts of the surface, the heavily shaded hill being frequently less in altitude than one bearing but few hachures, owing to the low angle of





FIGS. 2 and 3.—Examples of Hachure Shading.

slope in the latter. It is therefore necessary, in addition to hachure shading, to print the heights of important points, so as to enable a fair estimate of the relief of the district to be made.

In many of the maps of the Ordnance Survey the slope of the ground is indicated by vertical hachures similar to those in Fig. 3, and in the case of the more hilly districts a very fair idea of the relief of the country is conveyed.

Other types of shading, both in black and in colour, have from time to time been employed in the production of relief maps, but it must be borne in mind that no system of shading, however elaborate, can do more than indicate the general character of the surface, without

furnishing any accurate means of measuring either slopes or heights, and therefore recourse is had, in all cases where accurate measurement is desired, to another system —viz. that of contouring.

A contour line is one drawn upon a map through all points having the same altitude; in other words, a contour line is the line of intersection between a horizontal plane and the surface of the country.

This may be illustrated as follows: The present shore-line of a country is the contour-line of zero, or sea-level, and were the sea to rise 50 feet the new shore-line so produced would coincide with the contour line of 50 feet, while a rise of sea-level of a further 50 feet would bring the water up to the 100-foot contour, and so on.

From the nature of a contour line it follows that it must be a closed curve, and that one contour cannot cross another. Two contours of different altitudes may converge as the ground becomes steeper and may run together so as to form a single line in the case of a vertical cliff, but they will separate and diverge where the cliff ends. The levels represented by the two lines will be one vertically above the other on the cliff face, and will consequently be coincident in their horizontal projection on the map.

Reading Contoured Maps.—When contour lines are drawn sufficiently near together, and are printed in such a manner as to be readily visible, they serve not only the purposes of accurate measurement, but form in themselves a species of hill shading which gives a good idea of the physical features of the district depicted, at a glance. This is well illustrated by the exquisite maps of the United States Geological Survey, and by those of some of our colonies.

In large-scale maps the contours are too far apart to serve the purpose of hill shading, and in such cases they are sometimes supplemented by some type of hachure, or by colour-shading.

Even in cases where the contour lines are far

apart, and no shading has been added, a study of the forms of the lines will give to the practised eye a clear indication of the form of the ground. Obviously, the more closely packed the contour lines, the more rapid is the slope, and where the curves of the lines are simple, the slope is a smooth one; but where the contours run in complex curves with frequent and sudden changes of direction, the country will be found to be broken.

The manner in which contours are related to the elevation, slope, and form of the ground is illustrated in Figs. 4 and 5.

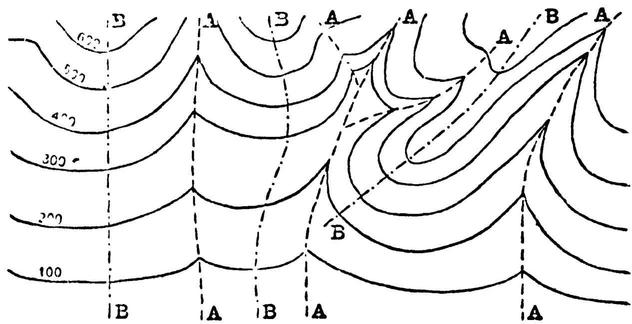


FIG. 4.—Contour Lines.

The following points with regard to contour lines are noted as being of importance in the reading of maps:—

(*a*) Before proceeding to the detailed study of the land forms, it is necessary to ascertain the contour interval, *i.e.* the vertical distance between successive contours, and to note whether this is constant throughout the whole vertical scale or changes, as is the case in many maps—*e.g.* in those of the Ordnance Survey on the scale of 1 inch to a mile, the first contour line is at 50 feet and the second at 100, after which the interval is 100 feet up to a height of 1000 feet, above which the lines are drawn at 1250 feet, 1500 feet, 1750 feet, and 2000 feet.

(*b*) Contour lines usually form a V-shaped curve where they cross a stream, the apex of the V pointing up-stream.

(*c*) The contours on projecting spurs of a hill are, except in the case of extremely sharp ridges, of a U-shaped character. Thus in Fig. 4 one would judge from the shape of the contours alone that the lines marked AA were the valleys and the lines BB the intervening spurs.

By means of contour lines it is readily possible to draw profile sections of the country, and the student should prepare a number of these, so as to become thoroughly familiar with the relations of contour lines to land forms. The method of drawing a profile section from a contoured map will be best illustrated by an example (see Fig. 5).

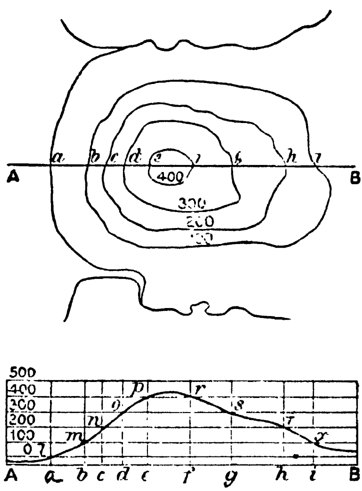


FIG. 5.—Contoured Plan and Section of a Hill.

Assuming that it is required to draw a section or profile of the country along the line AB, proceed as follows: Draw a horizontal base line equal in length to AB, and mark upon it the distances A*a*, A*b*, A*c*, &c., equal to the corresponding distances on the map; at each of the points *b*, *c*, *d*, &c., erect perpendiculars *bm*, *cn*, *do*, &c., proportional to the heights above sea level of the contour lines which intersect the line AB on the map in the points *b*, *c*, *d*, &c., and lastly join up the points A, *l*, *m*, *n*, &c. The curved line thus produced will approximately represent the profile of the country along the line AB.

It must be remembered that such a profile is only strictly correct at the points *l*, *m*, *n*, &c., and that the shape of the curve between these points is only approximately correct. The positions of the contour lines on the map tell us that there is a fall of level of 100 feet between

c and *b*, but they do not indicate whether this fall is distributed equally along the whole distance, or is confined to the neighbourhood, say, of *c*, the remainder of the distance to *b* being level.

With regard to the vertical scale chosen to represent the heights *bl*, *cm*, &c., the draughtsman will be guided by the purpose for which the section is required, but in all cases the scales, both horizontal and vertical, should be recorded upon the drawing, and wherever possible a section in which an exaggerated vertical scale has been employed should be accompanied by one drawn to true scale, that is, with the same vertical and horizontal scales, as this alone can give a correct idea of the form of the ground.

In the making of geological sections which will be referred to at length in the following chapters, too much importance cannot be attached to the true scale, as any exaggeration of the vertical scale not only distorts the profile, but renders necessary a corresponding distortion of the geological structure.

For ascertaining the visibility of points one from another, contours are again useful. On a concave slope all points will be readily visible either from the summit or the base, while in the case of a convex slope this will not be the case. [A concave slope can be recognised upon a contoured map by the fact that the contours are nearer together towards the top of the slope, while a convex curve is indicated when the distance between the contours decreases towards the foot of the declivity.]

The importance of the form of a slope, in the case of the establishment of a defensive position on the summit, will be seen when it is remembered that, in the case of a concave slope, an attacking force would be visible and consequently under fire throughout the whole ascent, and further would have to climb the steepest portion of the hill when at short range.

There are two methods in use for describing the steepness of a slope: it may be expressed as an angle, in

degrees from the horizontal, or as a gradient. The latter is usually expressed as a fraction; thus 1/325 (or 1 in 325) would indicate a rise or fall of 1 foot in a horizontal distance of 325 feet.

The two methods are connected in the following way: An inclination of 1° is a gradient of 1 in 57·29 or 1/57·29, since 57·29 is the natural cotangent of 1°. A slope expressed in degrees may therefore readily be converted into a gradient by means of a table of natural cotangents. (See Table, p. 130.)

For small angles, up to, say, 10°, the gradient may be obtained by dividing the cotangent of 1° by the number of degrees in the angle; thus the gradient corresponding to an angle of 2° is approximately 1 in $\frac{\cot. 1^\circ}{2} = \frac{57 \cdot 29}{2} = 28 \cdot 6$, and for 3°, 1 in $\frac{\cot. 1^\circ}{3}$ or 1 in $\frac{57 \cdot 29}{3} = 19 \cdot 1$, and so on. This rule cannot be employed for larger angles, as the error rapidly becomes greater as the size of the angle increases; in fact, it is better to employ the table of natural cotangents in all cases.

It is useful, where much work is to be done with maps of one and the same scale, to construct what is known as a scale of horizontal equivalents, as by its means degrees of slope of the ground may readily be determined. The term "Horizontal Equivalent" is used to express *the horizontal distance in which a given difference of level will occur, at a given degree of slope;* and to construct a scale of such equivalents, the difference of level chosen as the basis will of course be the contour interval of the map upon which it is to be used. The scale must also be drawn to the scale of the map.

Thus, suppose it is desired to deal with a map on the scale of 6 inches to a mile, with contours every 25 feet proceed as follows:—

$1^\circ = 1$ in $57 \cdot 3$ or 25 in $57 \cdot 3 \times 25 = 1432 \cdot 5$.
$2^\circ = 1$ in $28 \cdot 6$ or 25 in $28 \cdot 6 \times 25 = 715 \cdot 0$.
$3^\circ = 1$ in $19 \cdot 1$ or 25 in $19 \cdot 1 \times 25 = 477 \cdot 5$.

Similarly the horizontal equivalents of 4, 5, 6, 7, 8, 9, 10, 12, 15, and 20 would be obtained, and these distances would then be plotted, on a scale of 6 inches to a mile, as in Fig. 6. By applying this scale to the map so that its length lies at right angles to the contour lines, and noting the scale division which corresponds to the distance between two neighbouring contours, we can at once read off the angle of the slope or the corresponding gradient.

Fig. 6.—Scale of Horizontal Equivalents, for a map on the scale of 6 inches to 1 mile, with a contour interval of 25 feet.

A useful adaptation of the contoured map is that coloured on the layer system, in which the spaces between successive pairs of contours are tinted differently. When possible the same colour, in washes of varying depth, should be used for this purpose, rather than different colours; but where the number of contours is large, shades of two colours may be used with good effect, as in the admirable maps, on a scale of 2 miles to an inch for England and Scotland, and of 4 miles to an inch for Ireland, published by Messrs. John Bartholomew & Co., in which all heights above 500 feet are in shades of brown, increasing in depth of tint upwards, while all ground between sea-level and 500 feet is tinted green, the depth of the colour increasing downwards. By this arrangement the pale shades of the two colours are brought together on the 500-foot contour, and the break is therefore not so marked as if the dark shade of one colour were in juxtaposition with the light shade of the other.

By a proper arrangement of the shades an idea of solidity may be given which renders the map almost equal to a relief model.

The importance of a good contoured map for geological purposes cannot be over-estimated; the form of the ground as indicated by the contours often gives valuable indications of its physical structure, while in all matters connected with

river development and capture, and with glacial lakes and their overflow channels, it is almost indispensable.

The sketch map which forms Fig. 7 illustrates the use of contour lines in the last-named connection, the position of the ancient overflow channels at AA being distinctly indicated by the contour lines. This example is taken from Professor Kendall's paper on the Glacier Lakes of the Cleveland Hills.[1]

The value of contour lines in geological mapping will be understood more fully when the methods of plotting outcrops have been discussed (see Chap. III.).

The Maps of the Ordnance Survey.—The Ordnance Survey of the United Kingdom ranks in the very fore-

FIG. 7.—Glacial Overflow Channels ("Dry Gaps"), AA, indicated by Contour Lines.

front of the national surveys of the world as regards the thoroughness and accuracy with which the field work has been conducted; but, unfortunately, until quite recently, it was far behind those of the United States and of Canada, as regards the style of printing of the maps. Of late years, however, several new editions of the maps have been published, and some of these, notably the coloured edition of the map on the scale of 1 inch to a mile $\left(\frac{1}{63,360}\right)$, leave little to be desired as regards clear-

[1] *Quarterly Journal of the Geological Society*, vol. lviii. pp. 471–571.

ness of the topographical details. Even in these newer editions, however, our maps are still inferior to those of the United States as regards the printing of the contour lines, which form such a prominent feature of the American maps.

The greatest defect in all the outline maps, that is, those without colour, is the manner in which these contours are printed. In many of the maps they are so indistinct as to necessitate the use of a reading lens in order that they may be traced; and even with this aid it is almost impossible to trace some of them across the stippled or shaded areas representing parks and plantations.

In consequence of their faintness it is necessary to trace them over with a coloured ink before they can serve the purpose of form-lines or give any general idea of the physical features of the district, an extremely laborious, and, as the writer knows from experience, a very tedious process.

The original purpose of the Ordnance Survey was military, but the maps have been so prepared as to give them the characters desirable for other uses, *e.g.* in agriculture, surveying, engineering, and other works, and for the purposes of local government, and of the Geological Survey.

It is not proposed to enter here into a full description of the characteristics or conventional signs employed in the Ordnance Maps, as these are published in a cheap and convenient form by H.M. Stationery Office.[1]

SCALES USED IN THE ORDNANCE MAPS.

(1) $\frac{1}{1,000,000}$, or 15·782 miles to 1 inch.

(2) $\frac{1}{633,600}$, or 10 miles to 1 inch.

[1] "Ordnance Survey Maps of the United Kingdom. A Description of their Scales, Characteristics, &c." By Colonel S. C. N. Grant, G.M.G., R.E., Director-General of the Ordnance Surveys. July 1908. (Price 6d.)

(3) $\frac{1}{253,440}$, or 4 miles to 1 inch.

(4) $\frac{1}{126,720}$, or 2 miles to 1 inch.

(5) $\frac{1}{63,360}$, or 1 mile to 1 inch.

(6) $\frac{1}{10,560}$, or 6 inches to 1 mile.

(7) $\frac{1}{2500}$, or 25·344 inches to 1 mile.

(8) $\frac{1}{1056}$, or 60 inches to 1 mile.

(9) $\frac{1}{528}$, or 120 inches to 1 mile.

(10) $\frac{1}{500}$, or 126·720 inches to 1 mile.

(1) *Scale of* $\frac{1}{1,000,000}$. This is a map of the British Isles, the hills being shaded in brown and the water coloured blue. It is issued unmounted in two sheets, but may also be purchased mounted as a wall map. It is a useful general map for purposes of reference, as it contains a large number of place names, but it is not suitable for class purposes, as it does not possess the necessary boldness of outline.

(2) *Scale of* $\frac{1}{633,600}$. In this map Great Britain and Ireland are published separately. There are two editions of the map, one in outline only, but with the water coloured blue, and the other with the hills shaded in brown. The map of Great Britain, outline edition, is issued in twelve sheets and the coloured edition in eight sheets, but either may be obtained mounted as a wall map.

The map of Ireland is published in a single sheet.

Like the smaller scale map just described, these are suitable for the library rather than for the class-room.

(3) *Scale of* $\frac{1}{253,440}$, *or* 4 *miles to* 1 *inch.* This is frequently spoken of as the "quarter-inch map," and is

published of the whole of the United Kingdom, but the style of the maps varies slightly in the different countries. There are two editions in the case of each country, (*a*) engraved in outline and (*b*) coloured with hills indicated in brown, both being published in sheets, the size of sheet being different in each of the three countries.

In the case of England, Wales, and Scotland, special county and district maps have been prepared by combining parts of two or more sheets of the general map.

(4) *Scale of* $\frac{1}{126,720}$, *or 2 miles to 1 inch.* Printed in colours with the hills and contours in brown, water in blue, principal roads sienna, and woods green, this map has been issued in forty sheets for England. It is contoured with a 100-foot vertical interval up to 1000 feet above datum level, and then with one of 250 feet, and a special edition, coloured on the layer system, is in course of publication.

The Scottish map is similar to that of England and Wales, but the publication is as yet incomplete.

A map of Ireland on this scale is in course of preparation, but no sheets have been issued as yet.

In addition to the ordinary sheet maps, special sheets of certain areas are also published.

(5) *Scale of* $\frac{1}{63,360}$, *or 1 mile to 1 inch.*

The "1-inch" map is, perhaps, the most generally useful of all the publications of the Ordnance Survey. It is issued in four forms for England and Wales, viz.:—

(*a*) In outline with contours.

(*b*) With hills shaded in brown.

(*c*) With hills shaded in black.

(*d*) Fully coloured.

In addition to the general map which is issued in sheets of 18 × 12 inches, there is a large sheet edition in course of publication in the style (*d*), and numerous special maps of the country surrounding some of the principal towns have also been issued, but these are not all fully coloured.

Scotland is published in four forms similar in most respects to the above.

In the case of Ireland there are again four forms, but these are not quite similar to the maps above described; they are as follows:—

(*a*) In outline with contours.

(*b*) With hills shaded in black.

(*c*) Coloured.

(*d*) In outline with boundaries of counties, and urban and rural districts in red.

This scale is the most suitable as a road map, and for all ordinary topographical purposes, and it forms the basis of the "1-inch" Geological Map, which is the chief publication of the Geological Survey.

(6) *Scale of* $\frac{1}{10,560}$, *or* 6 *inches to* 1 *mile.*

This map is published for the whole of the British Isles, and is in outline only. The contouring varies considerably in different areas, as regards the vertical interval, and some parts of Scotland and of Ireland are not as yet contoured at all.

Thus in Lancashire, Yorkshire, and some of the southern counties of Scotland, contours are shown to the highest levels at intervals of 100 feet, with interpolated contours at 25-foot intervals. Unfortunately these maps with 25-foot contours are few in number, and any one who has worked upon surface features in one of the favoured districts, will find his labour greatly increased when he goes elsewhere.

As has been already stated, the contours on some of the maps are very indistinct and difficult to follow, and this is a point which it is hoped will be improved when the revised editions now in progress are issued.

For geological field work, the 6-inch map is extremely useful, and no mapping should be attempted by the student on any smaller scale.

As will be more fully described later, the sheets of the 6-inch map are arranged in counties, which causes some

trouble when working on areas which include parts of more than one county; the exigencies of projection, however, render some such arrangement necessary. c

(7) *Scale of* $\frac{1}{2500}$, *or* 25·344 *inches to* 1 *mile.*

This is the plan of most use to the landowner and the farmer, and is also largely employed by engineers as the basis for work on a larger scale. It is published only for the cultivated districts of Great Britain, the survey of the cultivated districts of Ireland being in progress.

The plans show numerous levels, but are not contoured. Field boundaries are shown distinctly, and on the newer maps, the areas of the various enclosures are given in acres and decimals of an acre. The map is of use for geological purposes in areas of great complexity, or where great detail is required.

(8) *Scale of* $\frac{1}{1056}$, *or* 60 *inches to* 1 *mile.*

This, and the larger scale maps next to be described, are generally known as "town plans," as they are issued only for the town areas. They are intended for the use of municipal engineers, but are also largely employed by Fire Insurance Companies, and serve a variety of other purposes.

The plans of London, Dublin, and Belfast are on this scale, as are the original plans of the towns of Lancashire, Yorkshire, and the South of Scotland, but these latter have been superseded by the $\frac{1}{500}$ scale.

(9) *Scale of* $\frac{1}{528}$, *or* 10 *feet to* 1 *mile.*

There are a few places only which have plans on this scale.

(10) *Scale of* $\frac{1}{500}$, *or* 126·720 *inches to* 1 *mile.*

Since the year 1855 it has been the rule to prepare plans of all towns of 4000 inhabitants and upwards on this scale, so that most of the principal towns of the United

Kingdom now possess such plans (London, Dublin, and Belfast excepted).

The scale is sufficiently open to indicate the positions and thicknesses of walls, and most of the town plans show objects connected with water-supply, lighting, and sewerage, such, for example, as hydrants, lamp-posts, man-holes, gulleys, tramways, telegraph poles, and the like. Levels are shown along the principal streets, and bench marks[1] appear at frequent intervals.

The ordinary maps are issued with the buildings stippled or cross-hatched in black, though some areas can also be purchased with the buildings in colour; but as this is put on by hand, such maps are costly.

The System of Numbering the Sheets of the Ordnance Survey.—Comparatively few people seem to know how to obtain an Ordnance Map, so it may not be out of place to give here a few details as to the general arrangement and numbering of the sheets.

Catalogues of the Survey Publications are published yearly in separate volumes for England and Wales, Scotland, and Ireland. They contain indices to all small-scale maps, and to the 6-inch and 25-inch maps of their respective countries, with the date of revision, size, and price of each map, together with a small specimen of each kind of map published.

Index maps for each scale separately may also be obtained at the cost of a few pence. They may be seen at the offices of the agents for Ordnance Maps in all the principal towns, or may be ordered, as may also the maps, through any post office in the United Kingdom, though in the case of small country offices the operation is frequently attended with some difficulty.

The system of numbering the sheets is simple, and in the case of the small-scale maps there will be no difficulty in ordering, once the key plan, or index, as it is called, has been obtained.

[1] See p. 19.

The 1-inch maps also are simple. They have one meridian for the whole of each country, and the lines separating the sheets are parallel and perpendicular to this, the country being thus divided into a series of rectangles, the numbers of the sheets running from north-west to south-east.

The larger-scale maps are prepared by counties, each county or group of counties having its own meridian, and in consequence of this there is issued a separate key-plan for each county, the sheets being numbered in the same direction as in the case of the 1-inch maps.

The basis of the large-scale plans is the 6-inch sheet, the sizes of the larger-scale sheets being so arranged that

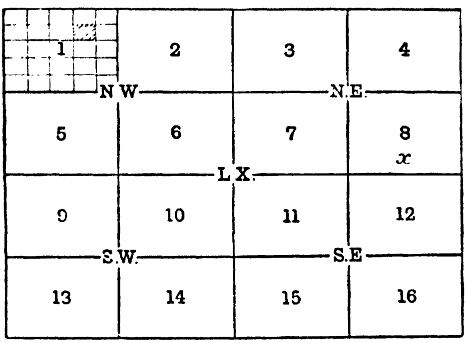


FIG. 8.—Diagram to illustrate the numbering of the sheets of the 6-inch and 25-inch Maps.

when they are reduced to the 6-inch scale they fit into the 6-inch sheets. Thus each 6-inch sheet corresponds to 16 sheets of the $\frac{1}{2500}$ map, while one sheet of the latter embraces 25 sheets of the $\frac{1}{500}$ plan.

The 6-inch map is for the most part issued in quarter sheets, though in Ireland it is still published in whole sheets. Where the whole sheets are issued it will be sufficient when ordering to give the name of the county and the sheet number, thus—Antrim VIII.

The quarter sheets are designated as N.W., N.E., S.W., and S.E. respectively, and the order for a single quarter sheet would therefore take the form—Hampshire IX. S.W.

The relation of the $\frac{1}{2500}$ and $\frac{1}{500}$ maps to the 6-inch sheet will be understood from the diagram (Fig. 8). Should, for example, the sheet marked x of the $\frac{1}{2500}$ plan be required, the order would take the form $\frac{1}{2500}$ ——shire LX. 8, while the shaded sheet of the $\frac{1}{500}$ plan would be indicated by $\frac{1}{500}$ ——shire LX. 1, 9, the sheets of this being similarly arranged.

Should it be found on consulting the plan that no number appeared in one of the spaces, it would be concluded that the sheet was not published.

Altitudes and Contours of the Ordnance Survey Maps.—In the case of Great Britain the altitudes are given in feet and decimals of a foot above mean sea-level at Liverpool. This was determined by a series of observations with a self-registering tide gauge, extending over a period of one month.

For Ireland another datum is used, namely, low-water mark of spring tides, at Poolbeg Lighthouse in Dublin Bay, and in the case of islands far from the coast local mean sea-levels have been determined, and the altitudes are referred to them.

In the 6-inch and $\frac{1}{2500}$ maps, surface levels are shown along the roads in feet thus, . 83, while on the 10-feet plans one decimal is given.

During the progress of the survey, altitude marks are cut on walls, buildings, and other objects. They are in the form of a broad arrow with a horizontal bar above, and are called "bench marks." They are indicated on the

plans thus, B.M. 152·8. The level, which is in feet, refers to the horizontal bar above the broad arrow of the bench mark, and the small arrow engraved on the plans marks by the position of its point the exact situation of the bench mark.

In the 1-inch and 6-inch maps altitudes are frequently attached to the trigonometrical stations, when they are on the tops of hills, or in other prominent places, thus △630·8.

The lowest contour is usually the 50-foot line, but in some flat, low-lying districts the 25-foot line is also given. The next contour above the 50-foot is the 100-foot, and they then proceed by 100-foot intervals up to the 1000-foot level, above which they appear only at intervals of 250 feet.

In Ireland the contouring is still in progress, and there is in consequence a number of maps published without contours, but the number is decreasing yearly.

The Maps of the United States Geological Survey.— It is impossible to leave this subject without referring to the excellent work done by the United States Geological Survey in the preparation of topographical maps, which forms part of its duties.

The work of preparing a topographical map of the United States was commenced about twenty-five years ago, but is, from the magnitude of the work, obviously still incomplete. The areas already mapped are not confined to any one State or area, but are scattered widely over the States and Territories, the survey having been commenced at a large number of points, as the districts became settled and the need for accurate maps arose.

Three scales are employed in the making of these maps, and these are chosen according to the amount of detail required to be inserted. The largest scale is $\frac{1}{62,500}$, which is very nearly 1 mile to 1 inch, and is used for those parts of the country which are thickly settled or important on account of their mining or other industries. The

general map of the less crowded areas is on a scale of $\frac{1}{125,000}$, or about 2 miles to 1 inch, a still smaller scale of approximately 4 miles to 1 inch $\left(\frac{1}{250,000}\right)$ being employed for the maps of the desert regions of the Far West.

The Survey is also preparing a geological map of the United States, and the topographical and geological maps of a quadrangle, as the areas depicted on a single sheet are called, are finally bound up, together with a description of the topography, geology, and natural resources of the district, to form a folio of the Geologic Atlas of the United States.

The maps are very fully contoured, the lines being printed in transparent brown ink, so as to be distinctly visible without being in any way unsightly or interfering with the other detail. The contour interval is varied according to the nature of the ground; thus in a mountainous district it may be as much as 200 feet, while in the plains the lines may be as close as 10 feet. The interval is, however, the same throughout one and the same map.

So close are the contours on many of the maps that they serve the purpose of hill-shading, and owing to the character of the ink employed, do this without detracting from the general clearness of the map.

II. Geological Maps

Geological maps contain, in addition to the ordinary details of the topography, information regarding the nature, inclination, age, and general relationships of the rocks forming the upper portion of the earth's crust. The exact form of the symbols employed to represent this information varies, of course, in different surveys, but the variation is not great, and therefore the general

descriptions and rules given in this and succeeding chapters as applicable to the maps of the Geological Surveys of the British Isles, will serve with but slight modification for the guidance of those who have to work with other geological maps.

In the first place, a geological map must show by means of colour or by suitable stippling the nature and extent of the rocks forming the surface of the ground. In addition, information must be given by means of suitable symbols of the position and extent of mineral veins, fractures, and other disturbances, and of the attitude of the beds of stratified rocks with regard to the horizontal plane and their relations to each other.

The Geological Survey of England and Wales is under the supervision of a director in London, while those of Scotland and Ireland are controlled from Edinburgh and Dublin respectively. This gives rise to slight differences as regards the size of the sheet and the nature of the colours and symbols employed, but the three surveys are carried on on similar lines, and the differences are trifling.

The geological maps are published on the scales of 25 miles to an inch, 4 miles to an inch, 1 inch to a mile, and 6 inches to a mile.

The 25-miles-to-an-inch map of the British Isles is published in a single sheet, and the areas occupied by the various geological formations are indicated in colour. The map may also be purchased uncoloured, but with the outlines of the various formations printed in black. In this form it is useful for class purposes, as single formations may be coloured in, thus giving prominence to their distribution.

The map on the scale of 4 miles to an inch, or the quarter-inch map as it is frequently called, is completed in the case of England and Wales, and a number of sheets has been issued in the case of Scotland, but Ireland is as yet unrepresented on the maps of this scale.

In the case of England and Wales there are two editions:

(*a*) "Drift," on which the surface deposits are indicated, and the colour appropriate to the solid rock which forms the foundation of a district only appears on the map where the rock actually crops out at the surface, or is only covered by a thin layer of vegetable soil, while the presence of glacial deposits, such as boulder-clay and gravel, river deposits, peat, and blown sand, are indicated by special colours; and (*b*) "Solid," in which the distribution of the solid rocks is indicated irrespective of the presence or absence of a covering of superficial deposits.

The maps are colour-printed, and are sold in sheets, but may be mounted to form a single map, the sheets of the "solid" edition of England and Wales forming an extremely handsome wall-map, which illustrates the structure of the country in a very striking manner.

The most generally useful geological map is that on the scale of 1 inch to a mile, of which "drift" and "solid" editions are issued.

The choice between the two forms will, of course, depend upon the purpose for which the map is required. For agricultural uses, drainage, and surface work generally, and for the study of the glacial deposits, the "drift" edition must be selected, but for all purposes for which it is necessary to gain information as to the general structure of a district, as in the case of water-supply from wells and boreholes, tunnelling, mining, and engineering generally, and for purposes of general geology, the "solid" map will be found most suitable.

In their most recent form the maps are issued in colour-printed sheets based on the corresponding sheets of the contoured edition of the Ordnance Map, but as these are only issued on the completion of the revised survey of each area, there are many districts for which they are not yet available, and in the case of these, the older hand-coloured maps must be used. These older maps are based on the Ordnance Maps, with hills shaded in black, and are without contour lines.

In the case of Ireland, the whole country has been sur-

veyed, and the 1-inch-to-a-mile maps are issued in the hand-coloured form, except about half-a-dozen special soil maps, which are printed in colour.

Six inches to a mile is the largest scale on which geological maps are published, and these are only issued for certain districts, such as the great coalfields and other important mining areas, but manuscript copies of most parts of the country can be inspected at the Survey Offices, where quotations may be obtained for manuscript copies of any area desired, provided that the survey has been conducted on this scale, which is now the case for most districts.

The maps on the scale of 1 inch to a mile and 6 inches to a mile not only show the surface distribution of the rocks, but by means of suitable symbols indicate the dip and orientation of the beds, the position and direction of lines of folding, and of fracture (faults), and the presence and nature of ore deposits, mines, shafts, quarries, wells, and other excavations.

The symbols employed to represent the structural features will be fully dealt with in the chapters on the interpretation of maps.

In addition to the maps, section-sheets on the scale of 6 inches to a mile are published, showing by means of profile sections the structure of the ground, and also certain vertical sections obtained from mines and bore-holes may be purchased for those areas where extensive mining work has been carried on.

On some of the sheets of the 1-inch map lately published sections are printed at the foot of the map, the lines of section being chosen so as to best illustrate the structure of the district, and occasionally also the vertical sections of the strata printed at the side of the map, and serving as an index to the colours employed, are drawn to scale, so as to indicate the relative and actual thickness of the beds.

The Geological Survey of the United States publishes a

very fine series of maps under the title of "Geologic Atlas of the United States," and this is one of the finest geological productions which have yet appeared. The atlas is issued in folios, each of which contains a number of maps of the same quadrangle, each map being designed to illustrate some special feature.

The maps contained in an ordinary folio are: a topographical map, a map of the areal geology—that is to say, a map similar to the "solid" edition of the English 1-inch survey—a map representing the economic geology, and a sheet of structure sections. In certain folios other special maps are included dealing with the distribution and depth of artesian water, and similar questions.

Geological maps are now published by the governments of nearly all the European countries, and surveys also exist in practically all our colonies. For general purposes the maps which are published by the International Geological Congress, and which will, when complete, form a Geological Atlas of Europe, are extremely useful.

CHAPTER II

SOME STRUCTURAL FEATURES OF THE EARTH'S CRUST

THE rocks of which the outer part of the earth is built up may be divided into three principal classes, viz.:—

(1) Igneous.

(2) Sedimentary or stratified.

(3) Metamorphic.

The rocks of the first class are those which have resulted from the cooling and consequent solidification of some mass of molten matter, and those resulting from the accumulation of fragmental volcanic materials, such as the so-called volcanic ash which collects in the neighbourhood of volcanic vents. The group includes lava which has been poured out from volcanoes and fissures, and masses of molten matter which have crystallised below the surface, and have subsequently been exposed by the removal of the overlying rocks through atmospheric agencies such as rain, frost, and rivers, or by the action of the sea.

Those rocks which have cooled and solidified at the surface of the earth are usually classified as volcanic, while those which have cooled at some depth are known as plutonic. The latter class is usually coarsely crystalline, as, for example, granite.

The fragmentary materials which accumulate in the neighbourhood of a volcanic vent, and which contribute so largely to the building up of the cone that is such a conspicuous feature of most volcanoes, may consist purely of igneous materials, as fragments of vesicular lava, volcanic glass and crystals, or they may include fragments of the country-rock, through which the pipe of the volcano

passes. They often lie in beds of irregular thickness, and resemble somewhat the sedimentary rocks in their mode of arrangement.

When, as has frequently happened, the volcanic outbreak occurred beneath the sea, the materials may be spread over wide areas by the action of the waves, and in this case occur in much more even layers, with much greater horizontal extent, than when they accumulate on land, and may only be distinguished from ordinary sediments by the nature of their component fragments. They are, in fact, midway between the two groups, being igneous in origin but sedimentary in their mode of accumulation.

The sedimentary rocks are the result of the action of the atmospheric agencies on pre-existing rocks, and are, therefore, for the most part, fragmental in structure, though some of them are the result of plant and animal life—for example, coal and limestone.

They have been accumulated as sediments in lakes, at the mouths of rivers, and on the floor of the sea, and were, therefore, usually formed in approximately horizontal layers, which have given rise to the bedded structure so common in rocks of this type. Some members of the group have been formed upon the surface of the land by the action of the wind, and in this case the bedding, though still present, is less conspicuous and more irregular than in the aqueous sediments.

The sediments are classified, according to their texture, as sand, sandstone, grit, clay, shale, slate, conglomerate, breccia, or by means of their chemical composition, as coal, dolomite, limestone.

Sand is the term applied to loose incoherent accumulations of fragmentary materials of moderately fine grain. It usually consists of fragments of quartz, but many other minerals may be present, and in rare instances build up the bulk of the deposit.

Sandstone.—A sand which has become coherent owing to the presence of some cementing material, such as oxide of iron, or calcium carbonate.

Grit is the name applied to sandstones in which the constituent grains are for the most part angular.

Clay is an extremely fine-grained deposit (consisting chiefly of the mineral kaolin or china clay, a hydrous silicate of alumina) which still retains sufficient of its original moisture to be plastic.

Shale.—A deposit of clay or fine silt, which has become somewhat hardened, and which possesses a well-marked fissile structure parallel to the planes of stratification.

Slate.—A fine-grained rock which has become indurated, and has developed a fissile structure, known as slaty cleavage, as the result of great pressure. The slaty cleavage may be developed at any angle with regard to the planes of stratification, which are frequently, indeed, partially or entirely obliterated.

Conglomerate.—This name is given to rocks consisting largely of fine-grained matter, but containing numerous rounded pebbles or boulders.

Breccia consists of an accumulation of angular rock fragments, embedded in a fine-grained matrix.

Limestone.—A rock consisting mainly of calcium carbonate, the result, in most instances, of the accumulation of the calcareous portions of shell-fish, corals, and other animals. Limestones may be either hard and crystalline, or soft and earthy in texture, as in the case of the chalk.

Coal is a name given to a group of rocks consisting principally of carbon, and too well known to need further description.

Under the heading of metamorphic rocks is grouped a variety of materials of widely diverse origin, which, however, possess one feature in common, in that they have been produced by the more or less profound alteration of some pre-existing rock, which may have been formed either by igneous action or as a sediment.

The alterations which come under the head of metamorphism have been brought about by pressure or by heat, or by a combination of these. The metamorphic rocks are usually highly crystalline, and in the case of

those which owe their present constitution to the action of pressure, are much sheared and crumpled.

The chief rocks belonging to this group are the gneisses and crystalline schists.

Stratigraphical Classification of the Rocks.—The rocks which form the earth's crust have been divided into a series of groups or "formations," according to their geological age, and a list of the principal subdivisions as they occur in Britain is given here for purposes of reference.

In the following table the rocks are arranged in their normal order, that is to say with the newest rock at the top, and the oldest at the bottom.

TABLE OF BRITISH FORMATIONS.

56. Recent Deposits	RECENT.
55. Glacial Deposits	PLEISTOCENE.
54. Forest Bed Series 53. Norwich and Red Crags 52. Coralline Crag	PLIOCENE.
51. (Absent from Britain)	MIOCENE.
50. Hamstead Beds 49. Bembridge Beds 48. Headon Beds	OLIGOCENE.
47. Barton Beds 46. Bracklesham Beds 45. Bagshot Beds 44. London Clay 43. Woolwich and Reading Beds 42. Thanet Sands	EOCENE.
41. Upper Chalk 40. Middle Chalk 39. Lower Chalk 38. Upper Greensand 37. Gault 36. Lower Greensand 35. Wealden Series	CRETACEOUS.
34. Purbeck Beds 33. Portland Beds 32. Kimeridge Clay 31. Corallian 30. Oxford Clay 29. Great Oolite Series 28. Inferior Oolite Series 27. Lias.	JURASSIC.

26. Rhaetic Beds	
25. Keuper Marl	
24. Keuper Sandstone	. . . TRIASSIC.
23. Upper Bunter Sandstone	
22. Bunter Pebble Beds	
21. Lower Bunter Sandstone	
20. Magnesian Limestone	. . . PERMIAN.
19. Red Sandstones	
18. Coal Measures	
17. Millstone Grit	
16. Yoredale Series	. . . CARBONIFEROUS.
15. Carboniferous Limestone	
14. Shales and Conglomerates	
13. Devonian and Old Red Sandstone	. . . DEVONIAN.
12. Ludlow Beds	
11. Wenlock Beds	. . . SILURIAN.
10. Llandovery Beds	
9. Bala Series	
8. Llandeilo Series	. . . ORDOVICIAN.
7. Arenig Series	
6. Tremadoc Slates	
5. Lingula Flags	. . . CAMBRIAN.
4. Menevian Series	
3. Harlech Grits	
2. Barren Sandstones and Volcanic Rocks	. . . PRE-CAMBRIAN.
1. Gneisses and Schists	

The names of the smaller groups given in the above table are those most generally in use in the British Isles, but it must be borne in mind that only the names of the larger groups, such as Cambrian, Silurian, &c., are of world-wide application. It is also important to remember that in older maps of the Geological Survey the rocks grouped in the table under the heading Ordovician are called Lower Silurian, while the term Upper Silurian is employed to designate the beds Nos. 10, 11, and 12, which above are called Silurian.

Stratification and Folding.—It has been stated on p. 27 that sedimentary rocks are, in most instances, laid

down in approximately horizontal layers, but it is within the experience of those who have examined rocks in the field, that horizontal stratification is, at all events in Britain, the exception rather than the rule. The beds of rock are frequently tilted or inclined, and in many cases the angle of inclination varies rapidly, so that very different inclinations, or "dips" as they are called, may occur in the same bed of rock within the limits of the same quarry or cutting. The dips are due to disturbance of the strata, subsequent to their deposition, and, in some instances, this disturbance has been so great as to throw

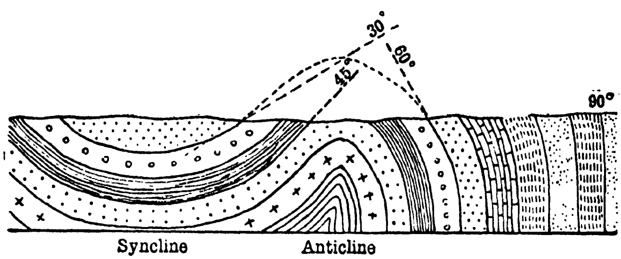


FIG. 9.—Inclined Beds formed by parts of Folds.

the beds into a vertical position, or, in extreme cases, to give rise to actual inversion.

The diagram (Fig. 9) is intended to illustrate the relationship of the various degrees of dip to each other, and it will be seen that the inclination of the strata is not due to simple tilting, but to folding; the names of the principal types of fold are indicated in the diagram. Cases also occur in which dip is due to a simple tilting of a block of the earth's crust, but these are, for the most part, to be explained by fractures of the strata, or "faults," which will be discussed later.

In addition to the simple anticlinal and synclinal folds seen in Fig. 9, other and more complicated arrangements of the strata occur in places where one system of folds is crossed by another, the simplest of these being the dome, or qua-qua-versal dip, in which the beds dip outwards in

all directions from a point, and the basin, in which the dips are inwards towards a centre.

The form of the folds also varies greatly, the following being the principal types:—

(*a*) The Jura type, so called from its prevalence in a part of the Jura Mountains, in which the anticlines and synclines are symmetrical as in Fig. 10, the general curvature of the strata approximating to the simple harmonic curve.

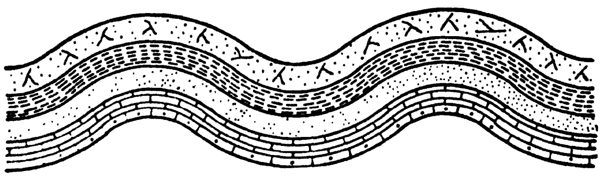


FIG. 10.—Folds of the Jura Type.

(*b*) The unsymmetrical fold (Fig. 11), in which the dip of one limb is considerably steeper than that of the other.

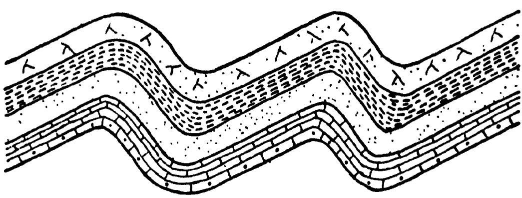


FIG. 11.—Unsymmetrical Folds.

(*c*) The overturned or recumbent fold (Fig. 12), in which actual inversion of the strata is to be observed in the upper limb, as the result of forward movement due to continued lateral pressure. In extreme cases recumbent folds may be transformed into reversed faults and thrust planes.

(*d*) Isoclinal folds are those in which the two limbs are crushed close together in such a manner that the beds on the two flanks of a fold are parallel to each other, and

the appearance in section is as in Fig. 13, *a* and *b*. The isoclines may be either vertical or inclined. In cases of isoclinal folding, there is often much difficulty in determining the true sequence of the strata, as beds are frequently repeated at the surface, and unless they have

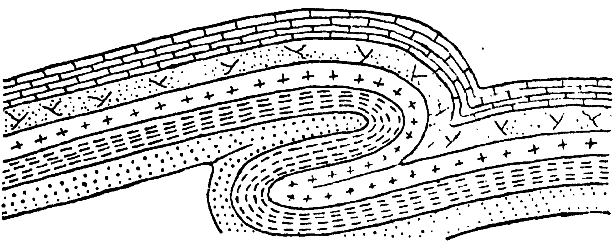


FIG. 12.—Recumbent Fold.

very well-marked characters, it is in consequence almost impossible to detect this repetition in the field.

Types of fracture other than thrust planes are produced by the action of gravity upon masses of the earth's crust detached from the surrounding blocks by shrinkage

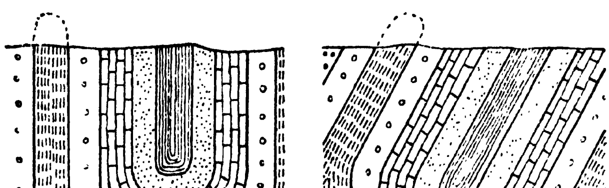


FIG. 13.—(*a*) Vertical Isoclinal Fold. (*b*) Inclined Isoclinal Fold.

or otherwise, and these are usually known as "normal faults," since they are the most commonly occurring type.

The fault plane is usually steeply inclined, and is frequently polished and striated in the direction of the movement which has taken place along it. The term "slickenside" is applied to such a polished and striated

surface, and it often serves to indicate the direction in which the movement has taken place.

From a study of slickensides, the existence of movements may sometimes be detected, when there is no actual displacement of the relative levels of the strata on the two sides of the fault plane. This may occur when, for example, successive blocks of strata have been displaced under the action of gravity in such a manner that the masses have come to rest at the same level, so that there is no remaining throw between contiguous blocks, although well-marked slickensides are to be seen.

Horizontal displacements are also indicated in the case of certain faults, which occur in connection with thrust planes, and which have received the name of "blatt" in Germany, a term which has been translated into English by the word "flaw." These flaws occur where the strata overlying a thrust plane have moved forward in successive blocks, either for the same or for different distances, and in either case the fault-plane of the flaw will be marked by slickensides with horizontal striations.

Faults of these last two classes are very difficult to detect in the field, as they do not necessarily bring different rocks into juxtaposition at the surface, though they possess all the objectionable qualities of other fractures from an engineering point of view.

The amount of throw of faults varies within wide limits. As has been seen, faults are known in which the relative vertical displacement is *nil*, while in the case of others it amounts to thousands of feet.

In other cases the amount of throw varies in one and the same fracture, and the fault may die out in one or in both directions owing to this cause.

The lateral extension of faults is very variable, in some cases a few hundreds of yards or less, in others many miles, the fractures either dying out or being cut off by other faults. In some instances the direction of faults is remarkably constant, and they traverse the country for

long distances in approximately straight lines. In others the curvature is considerable, reaching a maximum in the boundary faults of cauldron subsidences, such as those which occur in connection with areas of volcanic rocks, as has been described by Messrs. Clough, Maufe, and Bailey in the Glencoe district of Scotland.[1]

In the study of many districts it is found that there is a prevalent direction of faulting, and that the main fractures are approximately parallel to each other, while they are not infrequently connected by cross faults running in various directions.

Since the sediments are built up from the materials derived from pre-existing rocks, it follows that portions of the earth's surface must have been undergoing denudation

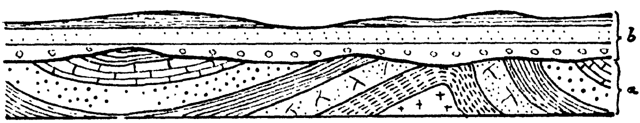


FIG. 14.—Section of an Unconformity.

in each of the geological periods, and also that no geological formation can be world-wide in its distribution.

The areas of denudation and of sedimentation have changed continually throughout geological time, and, in consequence, it has frequently happened that sediments have been deposited upon the denuded remnants of pre-existing strata. In cases of this kind there is a more or less marked discordance in the attitude of the strata in the two formations, and the junction between them is said to be unconformable. Thus, in Fig. 14, the strata labelled *a* had been laid down in a horizontal position and then tilted up so as to form land; subsequently they suffered denudation, and were again submerged, and the formation *b* was deposited upon them.

Unconformities vary widely, both as regards the degree of discordance of dip between the two formations, the form

[1] *Quarterly Journal of the Geological Society*, vol. lxv. pp. 611-678.

of the surface of separation, and the area over which they extend. The degree of discordance may vary in one and the same unconformity, as seen in the figure. Cases are known in which the difference of angle is as much as 90°, while in others it is so small that it cannot be detected within the limits of one section, but is only made clear when the boundary is traced over considerable areas, and it is discovered that the lowest member of the upper series rests successively upon different portions of the lower.

The character of the surface of separation depends upon the kind of denudation to which the surface of the older rocks has been subjected, and partly on the nature of those rocks. Sub-aerial denudation gives rise to irregular surfaces of hill and valley, while marine erosion produces a gently sloping and but slightly undulating plane.

CHAPTER III

DENUDATION AND THE RELATION OF OUTCROPS TO CONTOUR LINES

CONFUSION frequently arises in the mind of the student between the dip of the strata and the inclination of the ground. The form of the surface, though due to a variety of causes, is mainly controlled by the hardness of the strata, and it must be borne in mind that an anticline is not necessarily a hill nor a syncline a valley. Similarly the downthrow side of a fault is not always lower ground than the upthrow side, nor does the presence of an upthrow involve the existence of an elevated tract. The hills and valleys and other features of the surface of the land are formed by the action of the various agents of denudation upon rocks of unequal resisting power, the general type of scenery existing in a district being due to the nature of the rocks occurring in it, and to the attitude, structure, and arrangement of those rocks. For example, other things being equal, a river will cut a narrow gorge in hard rocks, but where it flows over softer strata, will produce a wide valley with a flat floor, over which it will meander, forming meadows and terraces.

In folded regions which have been long exposed to denudation the mountains are frequently found to possess a synclinal structure, and the valleys to occupy the lines of the anticline, owing to the fact that the rocks in the synclines are hardened by compression, while the tops of the saddles are weakened by stretching, the result being that after long-protracted denudation the anticlines have not only been cut down to the level of the synclines, but the latter, owing to the superior hardness of their strata,

have been left as hills, while the intervening anticlines have been still further cut away to form valleys (Fig. 15).

In the same manner the upthrow side of a fault is not necessarily high ground. In this case the surface features are due to rocks of different hardness being thrown into juxtaposition by the fault, and to the agents of denudation having acted more rapidly upon the softer than upon the harder material.

It is true that faults of recent occurrence occasionally produce directly a scarp or terrace, but these are of small elevation, and are quite insignificant features in the landscape, and further, they are of short duration, being rapidly obliterated by denudation.

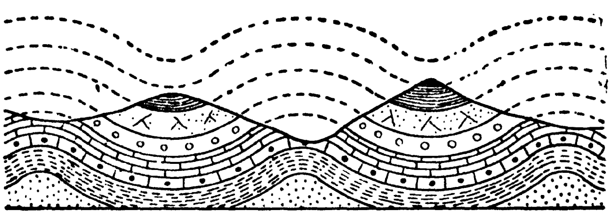


FIG. 15.—Synclinal Hills and Anticlinal Valleys.

Ranges of hills, and even mountains, in which the ridges are anticlinal, are also to be found—as, for example, the Pennine Chain; still the majority of the surface features, and also the minor detail of the landscape, are due to the various degrees in which the different rocks possess the power of resisting the agents of denudation.

It is, on this account, most important that there should be no misunderstanding as to the terms which are used to indicate the form of the surface of the ground and those descriptive of the attitude of the strata. Thus the terms hill, valley, and slope must be clearly distinguished from anticline, syncline, and dip, the former group being applied to the surface of the country and the latter to the surface of the beds of rock of which it is built up.

It is only after considerable practice that it becomes possible to form a general idea of the structure of a piece of ground from the shape and relations of the variously coloured areas which indicate upon a geological map the surface distribution of the rocks, but it is desirable at this stage to study the principles which determine the relationship of the boundaries of these areas to the contour lines which indicate the form of the land.

The simplest imaginable case, but one of rare occurrence, is where the surface of the country and of the strata are parallel to each other, as, for example, a level plain made up of horizontal strata, in which case the whole surface of the ground would consist of one and the same bed of rock, and the map would be of the same colour throughout. A similar result would be produced in the case of a uniformly sloping surface made up of a bed of rock of equal and parallel inclination.

As has been stated above, these conditions are rarely if ever encountered in nature except over very limited areas, and we must therefore turn our attention to the more complex cases which result from the intersection of discordant surfaces.

The area over which a bed of rock comes to the surface of the ground is called its *outcrop*, and we shall now proceed to study the relations which the forms of these outcrops bear to the form of the ground and to the dip of the strata.

The simplest case has already been considered, and it will at once be realised that if our geological map is differently coloured in different parts, either the surface of the ground is not level, or the beds are no longer horizontal. In the great majority of cases, in fact, neither of these conditions will be fulfilled, and as a result outcrops of varying degrees of complexity, and with divers relations to the contour lines, will result.

Firstly take the case of a horizontal stratum. This will be indicated upon the map by the symbol +, and a moment's consideration will make it clear that the outcrop

will be bounded by contour lines whose vertical interval is equal to the thickness of the bed.

It will be simpler to consider the bed of rock to be a plane, that is, to have no thickness, and of course the outcrop of this will be a line. Thus we may say that the outcrops of horizontal planes are contour lines. In this case the complexity of the outcrop will vary in accordance with the complexity of the surface, being simple where the ground is smooth, and irregular where the surface is hilly or broken.

Still retaining the supposition that the surface of our bed of rock is a plane surface, we will now investigate the effect of *dip* upon the form of the outcrop, and will suppose that the angle of dip is gradually increased from 0° to 90°, that is, from the horizontal to the vertical.

As the dip increases the lines of outcrop will depart more and more widely from the contour lines which they will now intersect, and as a general rule they will vary in the direction of greater simplicity as the dip increases, until when verticality is reached the outcrops will be straight lines passing over the surface of the map in the direction of the strike of the beds, irrespective of hill or valley. (See p. 50.)

In nature the surface of a bed of rock is rarely a plane surface, and often departs widely from that condition; consequently the dip varies rapidly from place to place, both as regards its direction and amount. It will nevertheless be useful to investigate the conditions which determine the forms of the intersections of planes with different degrees of inclination, as by that means experience will be gained, which will be found invaluable when the more complex cases of intersections between complicated surfaces, such as those found in nature, have to be studied.

The case of two plane surfaces is simple. Let us suppose that in Fig. 16 we have two surfaces, of which the two sets of parallel lines are the contours, projected vertically on to the plane of the paper, and that both planes cut the plane of the paper at the point A. The

dip arrows B and C represent the direction of dip of the two surfaces. The vertical interval between the contours will be considered as being the same in each case, and from this it will follow that the plane C dips more steeply than B, the contours being closer together on C.

The figures attached to the contours indicate their vertical distance above or below A which is, of course, a point common to the two inclined planes and to the plane of the paper, which represents the horizontal plane of the map. The problem now resolves itself into the finding of the position of other points common to the two inclined planes and joining them by a line.

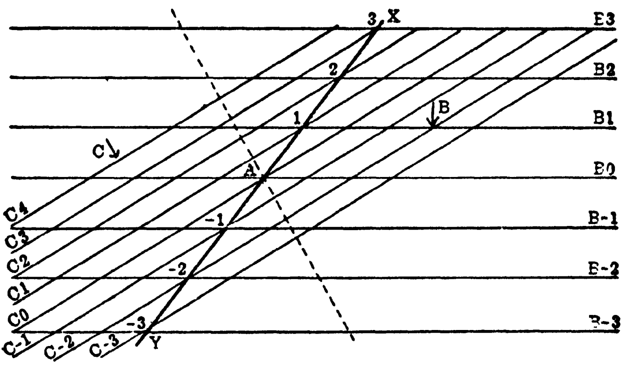
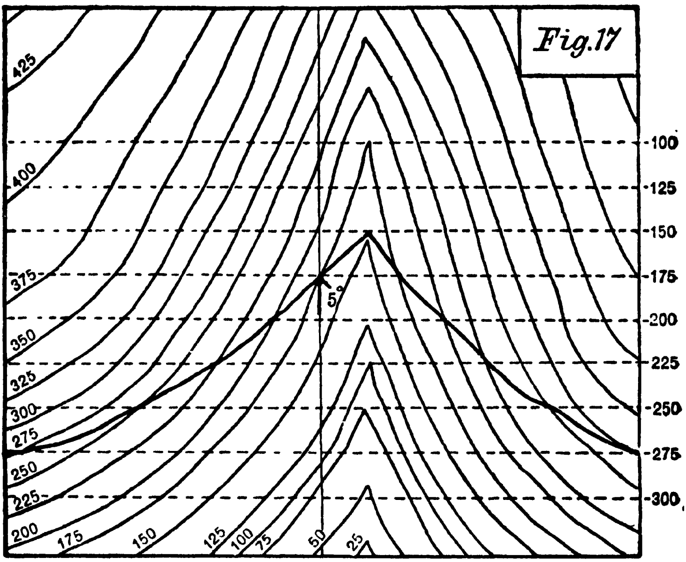


FIG. 16.—Projection of the Line of Intersection of two Plane Surfaces whose Dip is given.

At all points along the line B1 the plane B is at a height of one unit above the paper, and the same is true of the plane C at all points along C1, therefore it follows that B and C will be at the same level at the point of intersection of the lines B1 and C1, which is therefore a point common to both planes; and the same is true of the points of intersection of the lines B2 and C2, B3 and C3, B - 1 and C - 1, and so on. Thus it will be seen that the points, 1, 2, 3, - 1, - 2, and - 3, are common points, and the line XY, drawn through these points, is the projection of the line of intersection of the two planes upon the plane of the paper.

The line of intersection of two plane surfaces is, as will be seen from the diagram, a straight line, and it will be gathered from this and the following examples, that the horizontal projection of the line of intersection of any two surfaces, whether plane or curved, may be drawn, provided that the contour lines of both surfaces are known.

The above method is sometimes employed in geological surveying to connect known points of an outcrop with



each other, over an area where the rocks are concealed by surface materials, such as a swamp or a forest.

The following examples will serve to illustrate the method, and also to indicate the varying relation of outcrop to contour, with varying amounts of dip.

In the diagrams of Figs. 17 to 22 the curved lines represent contours projected on to a map, *i.e.* the ordinary contour lines, while the bed of rock whose outcrop it is desired to plot is supposed to possess a plane surface. The map used as the basis of these diagrams is on a scale of

6 inches to 1 mile, and the contour interval is 25 feet. The dips are given in degrees as in an ordinary geological map, and the point of the arrow at the centre of the diagram is one point in the outcrop. The problem now resolves itself into (*a*) drawing upon the map the horizontal projection of contours with a vertical interval of 25 feet upon the surface of the bed of rock, and since the surface is plane these will be straight lines parallel to the strike, and (*b*) joining up the points of intersection of corresponding contours.

We will suppose that it is desired to draw the outcrop of a bed of rock upon the contoured map (Fig. 17), and that one point in this outcrop is marked by the point of the dip arrow, and that the dip is 5°. The method of procedure is as follows: Produce the shaft of the arrow in both directions to the limits of the map. This line will be in the direction of the dip. Through the point of the arrow draw a line at right angles to the last. This will indicate the direction of strike of the bed, and, of course, all contours on the surface of the bed will be parallel to it. The contour interval on the map is 25 feet, and we must now ascertain the distance in which the bed will rise or fall 25 feet. The angle of the dip is 5°, and we ascertain from our tables that the natural cotangent of 5° is 11·43. That is to say, the bed will possess a gradient of 1 in 11·43.

The bed falls 1 foot in 11·43 feet, and will therefore fall 25 feet (the contour interval) in $11{\cdot}43 \times 25 = 285{\cdot}75$ feet.

Now lay off on the dip line divisions equal to 285·75 feet, in both directions from the point of the arrow, and through the points thus obtained draw a series of lines parallel to the strike. These will be the 25-foot *stratum contours* required, and it now only remains to mark the points of intersection of corresponding contours, and through these points to draw the outcrop.

It must be remembered in conducting this last operation that the outcrop cannot cross a contour line except

at one of these points of intersection of a *stratum contour* with the corresponding *surface contour.*

The point of the dip arrow touches the 175-foot surface contour, and the strike line drawn through it will therefore be the 175-foot stratum contour, as indicated in the margin of the map.

In the examples, Figs. 17 and 18, it will be noticed that the dip of the stratum is opposed to the slope of the

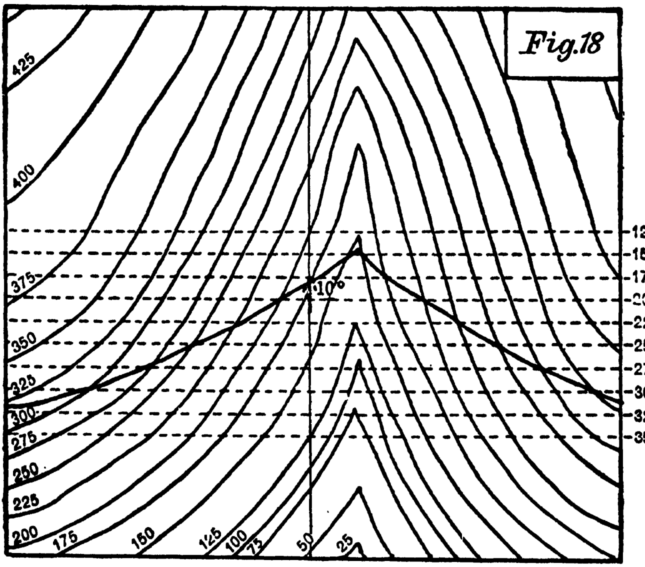


Fig. 18

surface, while in Figs 19 to 22 the dip runs in the same direction as the slope, and it is instructive to observe the forms of outcrop characteristic of each arrangement.

Thus in Figs. 17 and 18 it will be seen that the outcrop is V-shaped where it crosses the valley, and that the V points up stream, being less pronounced with the higher dip than with the lower. With still higher angles the line would become progressively straighter, until, at 90° dip, it would become a straight line.

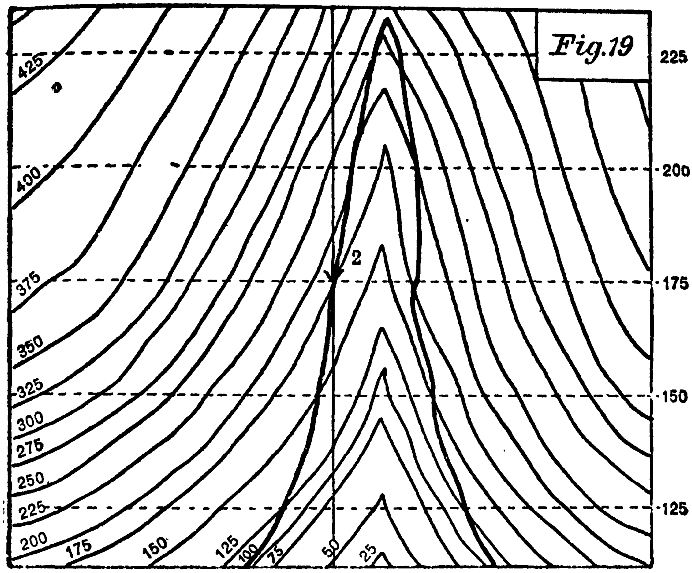


Fig.19
425
400
375
350
325
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275
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175
150
125
100
75
50
25
2
225
200
175
150
125

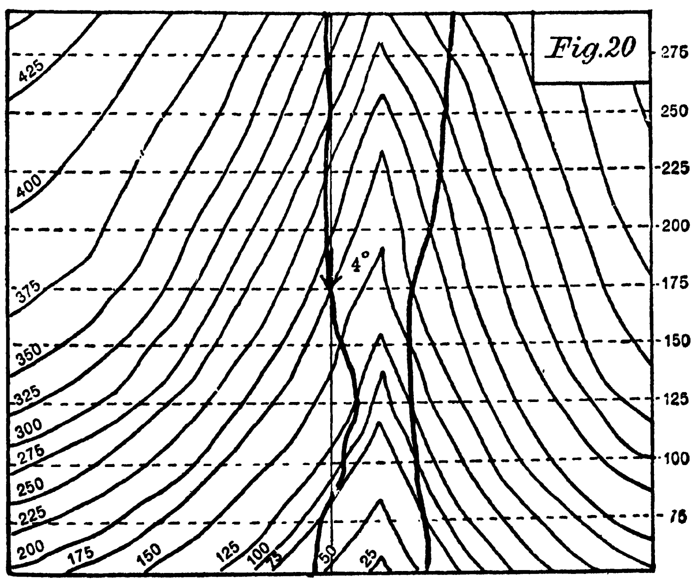
Fig.20
425
400
375
350
325
300
275
250
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200
175
150
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100
75
50
25
4°
275
250
225
200
175
150
125
100
75

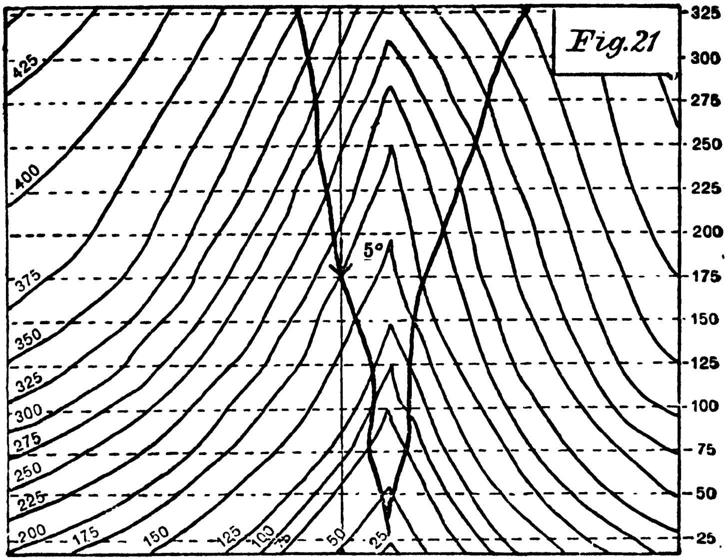


Fig. 21
325
300
275
250
225
200
175
150
125
100
75
50
25
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
5°

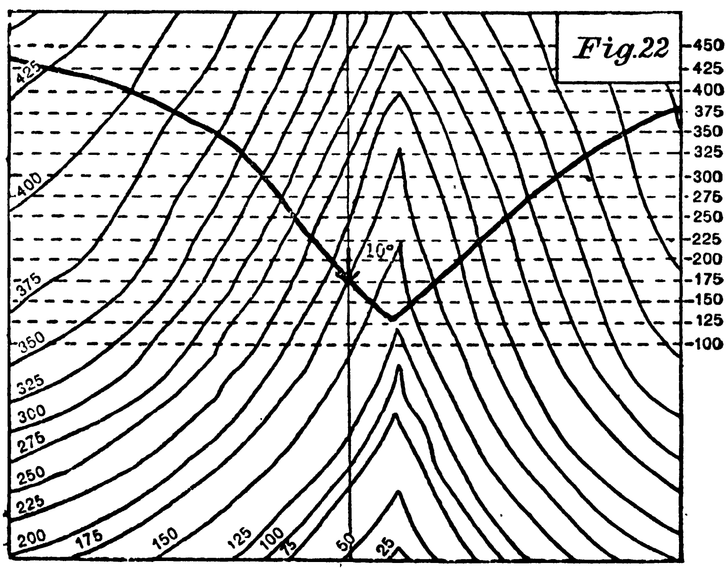


Fig. 22
450
425
400
375
350
325
300
275
250
225
200
175
150
125
100
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
10°

In Fig. 19 it will be noticed that the V still points up stream, although the direction of the dip (2°) is reversed.

With a dip of 4° (Fig. 20) the outcrop becomes duplicated, and is represented by approximately parallel lines on opposite sides of the valley. This is because the dip is now approximately *equal* to the slope of the surface.

Fig. 21 represents a dip of 5°, and it will be seen that the point of the V is now down stream, the dip of the bed of rock being greater than the slope of the valley. Fig. 22 indicates that the V still points down stream with higher dips, and that it becomes less pronounced as the dip increases, until, of course, when 90° is reached, the outcrop again becomes a straight line coincident with the strike.

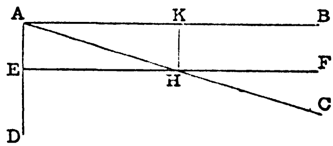


FIG. 23.

To summarise, the V points up stream in all cases in which the dip is opposed to the slope, but when the dip is down stream the V will also point in that direction, except when the slope of the surface is less than the dip of the stratum.

In the absence of a table of cotangents the horizontal interval for the stratum-contours may be ascertained graphically as follows (Fig 23): Draw an angle BAC equal to the angle of dip, and from A draw AD at right angles to AB, and mark off AE equal to the contour interval (say 25 feet) on the scale of the map. Draw EF parallel to AB and cutting AC in H, and from H draw HK perpendicular to AB. AK will be the horizontal interval required.

A development of this method can be employed in the case of strata whose surfaces are not plane but are curved in one direction only, as, for example, a simple anticline or syncline.

It will first be necessary to draw a section of the fold to scale. Let ACB in Fig. 24 be such a section, AB being

horizontal and C being a point on the axis of the fold. From C draw CD at right angles to AB, and from C mark off CE, EF, FG, GH, &c., equal to the contour interval.

Through E, F, G, and H draw lines parallel to AB, cutting the curve in *l*, *m*, *n*, *o*, *p*, *r*, *s*, and *t*, and from these points draw *s*1, *p*2, *n*3, &c., perpendicular to AB.

The distances D-5, 5-6, 6-7, 7-8, 8-B, D-4, 4-3, 3-2, 2-1, and 1-A will be the required horizontal intervals for the stratum contours, which will be straight lines parallel to the axis of the fold. An example of this kind is fully worked out in Fig. 25.

In the diagram (Fig. 25) the line ADB is the axis or strike of a synclinal fold, and C′D′E′ at the side of the

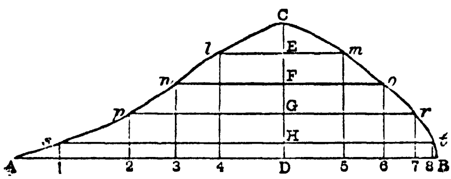


FIG. 24.

map is a section of the fold along CDE, C′E′ representing the section of a horizontal plane. In drawing the section, which may, of course, if necessary, appear upon the surface of the map, C′E′ must be coincident with or parallel to CE. Draw D′X perpendicular to C′E′ and mark off from D′ upon D′X a series of 25-foot intervals (the contour interval), and through the points thus obtained draw lines parallel to C′E′ to cut the curve. Finally through the points of intersection of these parallel lines with the curve draw lines across the map parallel to AB the axis of the fold (the dotted lines in the figure).

A moment's consideration will show that these are stratum contours, and we can now proceed to draw the outcrop through their points of intersection with the corresponding surface contours.

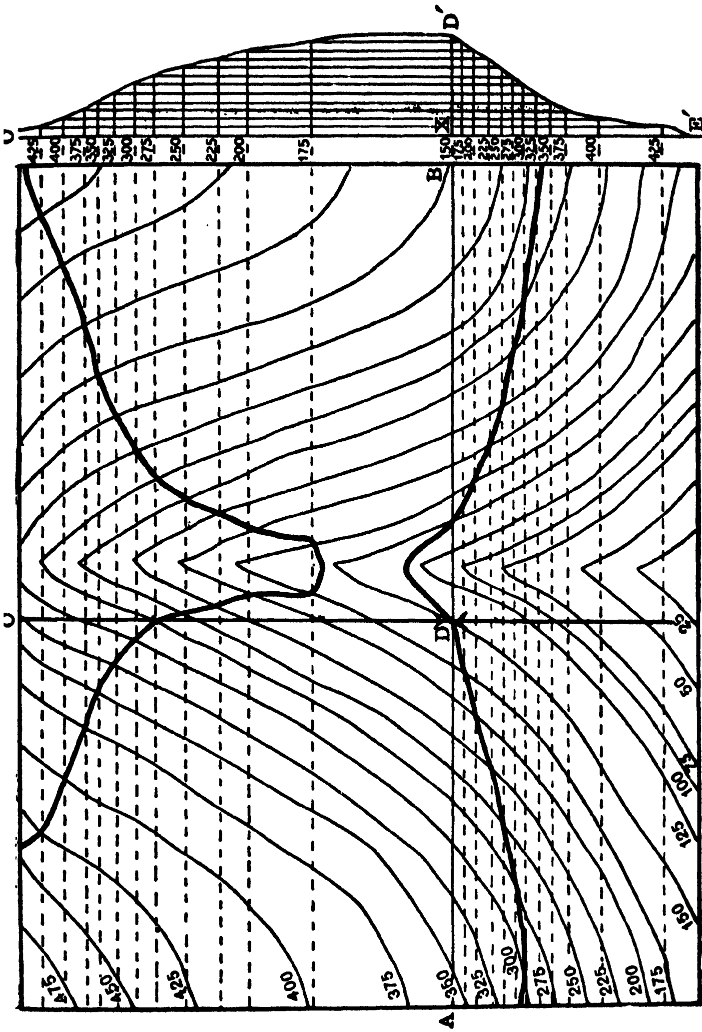

C
D′
X
E′
B
C
D
E
A
425
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
450
475

FIG. 25.

CHAPTER IV

INCLINED AND FOLDED STRATA IN PLAN AND SECTION

THE interpretation of geological maps must now be considered, and in this subject the familiarity with regard to the relation of outcrops and contour lines, gained by means of the exercises suggested in the preceding chapter, will be found to be of considerable service.

Firstly, it is desirable to become perfectly familiar with the meaning of certain terms relating to beds of rock and to features produced by denudation.

Dip and strike are terms which have already appeared in Chapter III., and it will be remembered that dip is the amount of inclination of the surface of a bed of rock with regard to the horizontal plane, and the direction of dip has been defined as the direction of steepest inclination upon that surface.

Strike is the direction at right angles to that of the dip and is that in which the beds possess no dip, their edges appearing horizontal in a strike section.

The thickness of a bed is measured at right angles to its surface, and is only coincident with depth when the strata are horizontal.

The term *outcrop* has already been defined, and *width of outcrop* is the width of surface occupied by the rock measured in the direction of the dip.

Unless it is clearly indicated upon a map that a bed of rock varies in thickness, it is usual to assume that the thickness is constant, and that variations in the width of the outcrop are therefore due to changes in the amount of dip, or in the slope of the ground.

The relationship of dip, depth, and thickness and the width of an outcrop will be seen from Fig. 26, where θ = angle of dip, a the width of the outcrop, b the thickness of the stratum, and c its vertical thickness or depth.

The width of the outcrop and the angle of dip being known, the other values may be calculated.

Thus $b = a \sin \theta$, and $c = a \tan \theta$.

The thickness of a bed of rock may therefore be obtained by multiplying the width of the outcrop by the sine of the angle of dip; and similarly, the depth at which a certain stratum will be met with in sinking or boring may be approximately determined by multiplying the distance from its outcrop to the sinking, measured in the direction of the dip, by the tangent of the angle of dip.

Further, the angle of dip may be calculated if either the width of outcrop and the thickness, or the width of outcrop and the depth are known.

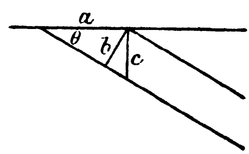


FIG. 26.

For $b/a = \sin \theta$, and $c/a = \tan \theta$, from which the value of θ in degrees can be obtained by the use of a table of natural sines or of natural tangents (Table II., p. 130).

An approximation to the true thickness of a stratum, sufficiently accurate for rough field measurements, may be obtained by means of what is known as Maclaren's rule, provided that it be applied only to angles of less than 45°. The rule is as follows: The thickness of inclined strata (in cases where the angle of dip does not exceed 45°) is approximately 1/12th of the width of the outcrop for every 5° in the angle of dip, or, in other words the number of degrees of dip divided by 60 expresses the ratio of the width of the outcrop to the thickness of the bed.

Example.

The dip of a bed is 10° and the width of the outcrop is 3600 feet.

Then $3600 \times 2/12 = 600$ feet is the thickness of the bed, or by the second method, $3600 \times 10/60 = 600$ feet.

By the trigonometrical method the true thickness will be found to be slightly less than that obtained by Maclaren's rule in the case of angles less than 30° and slightly greater when the dip exceeds 30°.

Thus in the above case, $3600 \times \sin 10° = 3600 \times 0{\cdot}174 = 626$, while with a dip of 40° Maclaren's rule gives $3600 \times 40/60 = 2400$ feet, and the trigonometrical method gives

$$3600 \times \sin 40° = 3600 \times 0{\cdot}643 = 2314 \text{ feet.}$$

In the practical work of drawing structure sections from a geological map, the readiest method of obtaining either the thickness or the depth of a stratum is by means of a graphic construction. It is only necessary to lay off with a protractor an angle equal to the angle of dip, *e.g.* ABC in Fig. 27, and then to mark off from B along BA, the width of the outcrop, say Bx. If the vertical depth of the bed is required, draw from x a line at right angles to BA, cutting BC at y. The line xy is the depth required.

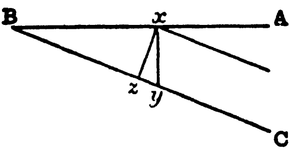


FIG. 27.

Where the true thickness is required, let fall from x a perpendicular to BC meeting it in z, then xz will obviously be the required thickness.

The problem of interpreting the structure and history of a district from a geological map usually resolves itself, at all events in the case of a beginner, into an attempt to draw structure sections along certain lines.

The choice of the position and direction of such lines, so as best to illustrate the main features of the area under consideration, is a matter of some difficulty at first, and in concentrating his attention upon the line chosen, or it may be, indicated by a teacher, or determined by the exigencies of an engineering problem, the student frequently misses important structural features, the evidence

for which may not be very clear along the line of section, but is easily detected in other parts of the map.

On this account no attempt should be made to draw a detailed section until the general features of the geology of the district included in the map have been mastered.

In the first place it is necessary to become thoroughly familiar with the order of superposition of the strata, whose outcrops are depicted, and with the meaning of the various colours and signs employed. The information necessary for this purpose may be obtained from the margin of the map, and particular attention should be given to the system of colouring, so that the student may be able to see at a glance which parts of the map are occupied by the newer sediments, and which by more ancient rocks.

Next it is important to note the main physical features of the surface, such as hills and valleys, plateaux and lowland plains, as their distribution may profoundly affect the forms of the outcrops, particularly where the dip of the strata is small.

The general dip of the rocks, as opposed to the extremely local dips indicated by the dip arrows, should next receive attention, and in this connection the main fact to be remembered is that the dip is towards the outcrop of the newer rocks. In other words, a traveller moving over the surface of a country in the direction of the dip will pass over newer and newer rocks as he proceeds upon his journey, while if he travels in the opposite direction, he will eventually reach the oldest rock exposed in the district. The forms assumed by the outcrops have been seen to be dependent upon the form of the ground and the inclination or dip of the strata (Chapter III.), and both these factors must therefore be taken into account in estimating the main structural features from the forms of the outcrops.

As an illustration of this the forms of outcrop indicated in Fig. 28 (*a*) would be consistent with the occurrence of horizontal beds on an isolated hill as in (*b*), or with the

existence of a basin-shaped arrangement of the strata on a plain (*c*).

In the examples and illustrations given in the present chapter, it is assumed that the country is free from faults, the effects of which will be discussed later.

The amount of the dip is usually indicated in figures (degrees) printed in proximity to the dip arrow, but it may also be estimated by the relation of the outcrop to the contour lines. Thus, if at one point an outcrop cuts the 600-foot contour and at another point 1 mile distant from the first cuts the 500-foot line, it is obvious that the dip is 100 feet per mile in the direction of the line joining the two points, which, however, may or may not be the direc-

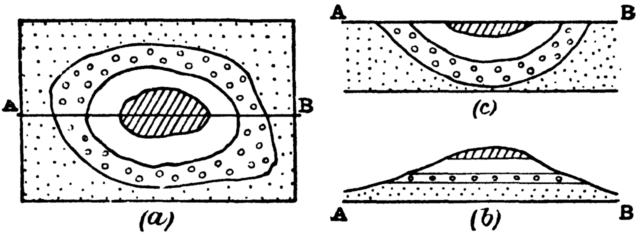


Fig. 28.

tion of maximum dip. 100 feet per mile is 1 in 52·8 or approximately 1°.

Another means by which an approximation to the dip may be obtained in cases where no dip arrow is near the line of section, is by comparing the width of the outcrop with that of the same rock in some other part of the area, where the amount of the dip is clearly indicated. This method, of course, assumes that the thickness of the stratum remains constant, and this assumption is made in all cases unless the map contains clear evidence to the contrary.

Example.

The width of an outcrop is 1 mile at a place where it is crossed by the line of a proposed excavation. There

is no dip arrow near this place, but at a point where a dip of 20° is indicated, the outcrop is only half a mile wide. Then taking θ as the angle of dip required, and assuming the thickness of strata to remain unchanged and the surface of the ground to be horizontal,

$$\frac{\sin\theta}{\sin 20^\circ}=\frac{1}{2}, \; i.e. \; \frac{\sin\theta}{\cdot 342}=\frac{1}{2}$$

$$\sin\theta=\cdot 342/2=\cdot 171.$$

On consulting a table of natural sines, it will be found that ·171 is the sine of 9° 51′, which is therefore the angle of dip required.

Apart from the actual calculation of the angle of dip, it may generally be assumed that where the outcrop of a

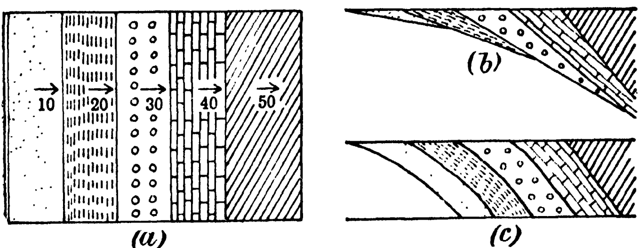


FIG. 29.

rock is narrow the dip is steeper than where the bed occupies a wider belt of country.

In this connection it must be borne in mind that inclined beds are in most instances parts of folds (see p. 31), and that, as a consequence, the dip of a bed varies continuously, and it must be remembered that the dip arrow and the figures attached to it merely indicate the dip at the *point of the arrow and at the surface of the ground.*

In drawing sections, therefore, care must be taken to preserve the thickness of the various strata unchanged, except where changes of thickness are clearly indicated. Thus in the example, Fig. 29 (*a*) it will be seen that the arrows on each bed of rock indicate a different amount of dip, but the beds must not be supposed to thin out as

indicated in the section (*b*), but to curve round gradually as in (*c*).

On steep slopes the outcrops of rocks usually appear narrower than on more level ground, and this must not be lost sight of in the above connection.

Unconformities.—The nature and mode of formation of an unconformity has been dealt with in Chapter II., and it is therefore only necessary to discuss the means by which its presence can be detected from a geological map.

The most obvious case is where there is a marked

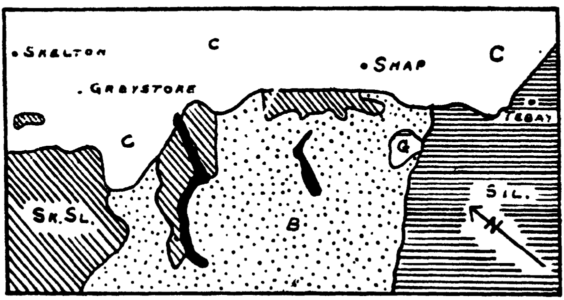


Fig. 30.—Geological Map of the district round Shap. *Sk. Sl.*, Skiddaw Slates. *B*, Borrowdale series. *Sil.*, Silurian. *C*, Carboniferous Limestone series. *G*, Granite.

difference in the direction of strike of the beds above and below the unconformity, and where, in consequence, the lowest bed of the upper series rests successively on different members of the older formation. An example of this is to be seen on the eastern side of the English Lake District (Fig. 30), which is covered by Sheet 3 of the "quarter-inch" map. Here it will be seen that the conglomerate at the base of the Carboniferous Limestone rests successively from N.W. to S.E. on Skiddaw Slates (Cambrian and Ordovician), Borrowdale Volcanics (Ordovician), and Silurian rocks, and that while the general strike of the older rocks is N.E. to S.W., that of the Carboniferous series is N.W. to S.E.

Thus when *discordance of strike* exists between two formations, we may conclude that their junction is an unconformable one. (See also Fig. 40.)

In many instances where the unconformity is of a less pronounced type, no discordance of strike can be detected from the forms of the outcrops within the limits of a single map, but it may be noticed that there is a discordance between the dips of the two formations. This *discordance of dip* may be one of direction or of inclination only, but in the latter case care must be taken to eliminate cases of change in the amount of dip due to folding. (See Figs. 9 and 29.)

Fig. 31 illustrates a case of discordance in the direction of dip, while in Fig. 32 only the amount of the dip is changed.

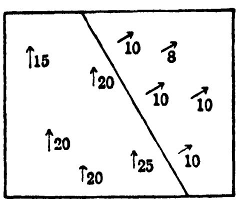


FIG. 31.

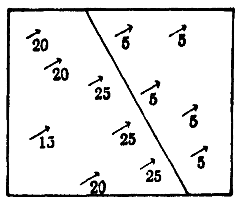


FIG. 32.

Where the older series has been sharply folded very complex cases sometimes occur, but the unconformity is then readily detected by the discordance of strike.

Faults and intrusive igneous rocks, when they are confined to the lower of two contiguous series of strata, are good evidence of unconformity, since they indicate movement and a considerable lapse of time between the formation of the two deposits.

If on making a preliminary examination of a map it be found that there is a formation or a subdivision absent from the district, the presence of an unconformity would be suspected, and this would be confirmed by some one of the above methods, unless the absence of the beds in question were found to be due to faulting.

Overlap.—In the case of strata deposited in the sea during a period of subsidence, the upper beds often extend beyond the limits of the lower owing to a larger area being submerged at the time of their formation. This phenomenon is known as *overlap*, and may give rise to considerable doubt as to the exact horizon at which an unconformity occurs. Thus in the section (Fig. 33) the bed *c* rests conformably on *b* but overlaps it, while both rest unconformably on *a*. If the left-hand side of the diagram were alone studied it would be concluded that the unconformity was at the base of the bed *c*, while in point of time it really occurs at the base of *b*.

Good examples of overlap are to be found amongst the Lower Cretaceous beds of the South-west of England, where the Gault overlaps the Lower Greensand to the

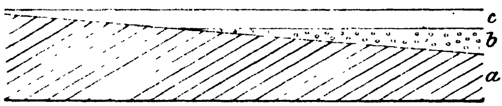


FIG. 33.—Overlap.

westward, and is in turn overlapped by the Upper Greensand. This is well seen on the quarter-inch survey, Sheet 19, in the neighbourhood of Devizes and Warminster, and on Sheets 17 and 22 near Chard and Honiton.

Lenticular Beds and Beds of Irregular Thickness.—It has been assumed up to the present stage that the beds of rock represented on our maps are of constant thickness, and this, though not strictly true, is sufficiently correct in most cases.

Instances, however, occur in which beds of rock thin out more or less rapidly in one or more directions. This is the case with certain limestones, probably of concretionary origin, which occur in lenticular masses,—with certain sandstones in the Coal Measures,—and with a variety of other rocks. Indeed, if traced sufficiently far, all rocks must thin out against a shore line or its equivalent.

Beds which thin out within the limits of a map are indicated in the margin in triangular instead of the usual rectangular form, and where a bed varies markedly in thickness this fact is also indicated.

Thinning out, and with more difficulty variation of thickness, may be detected from the forms of the outcrops, but in the latter case due care must be exercised in allowing for variations in the width of the outcrops due to changes in the amount of dip or in the slope of the ground.

An extremely interesting case of the thinning out of successive beds is to be found in the district round Market Weighton in Yorkshire. Here there is an anticlinal fold striking east and west, which was in movement during Jurassic times, with the result that all the rocks of that period thin out as they approach the axis, so that on the crown of the arch only the Lower Lias occurs, and that in an attenuated form, while to the north and south the Middle and Upper Lias and the various members of the Oolitic series appear in succession and thicken as the axis is left behind. The whole is overlapped by the Red Chalk (= Greensand and Gault) which at Goodmanham rests directly on the Lower Lias (quarter-inch map, Sheet 7, and 1-inch map, Sheet 72).

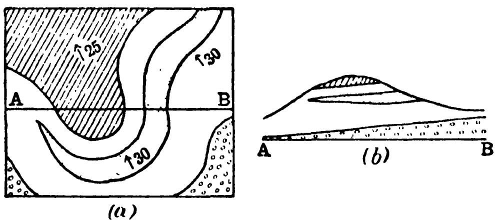


FIG. 34.—Thinning out of a Bed of Rock.

Thinning out can be detected upon a map by the gradual narrowing and eventual disappearance of the outcrop of the bed or beds affected (Fig. 34, *a* and *b*).

Escarpments.—During the denudation of inclined strata the harder beds will eventually come to stand up

above the softer ones, and the features called "escarpments" will be produced (Fig. 35), the short steep faces being called *scarps* and the more gentle ones in the direction of the dip, *dip-slopes*.

FIG. 35.—Section of Escarpments.

The escarpments of hard rocks are always steep, and in some instances they are vertical or nearly so.

Outliers.—It frequently happens during the wearing back of a scarp slope by the agents of sub-aerial denudation that owing to local conditions parts of the escarpments are left standing out as detached hills, and when these consist of a rock newer than those by which they are surrounded they are called outliers (Fig. 36). Outliers

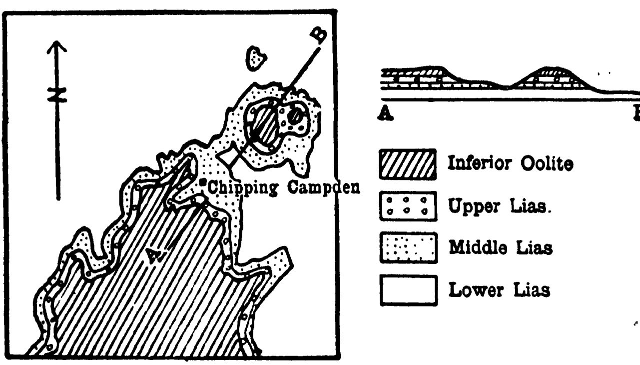


FIG. 36.—An Outlier in Conformable Strata.

are features of very common occurrence, and may be seen in considerable numbers along the northern face of the Cotteswolds, from which the example in Fig. 36 is taken (quarter-inch map, Sheet 15).

Outliers may also be produced during the denudation of a plateau, as is the case with Ingleborough and a

number of the surrounding hills in North-west Yorkshire (1-inch map, Sheet 50).

The strata forming an outlier may rest either conformably or unconformably on the rocks below. Fig. 36 is an example of a conformable outlier, while Fig. 37, which is taken from County Antrim, shows a case of an unconformable outlier at Knockladye (1-inch map, Sheet 8).

Another type of outlier is that in which the newer rock lies in a hollow denuded in the surface of the older strata, as in the case of the Lenham Beds (Pliocene), which

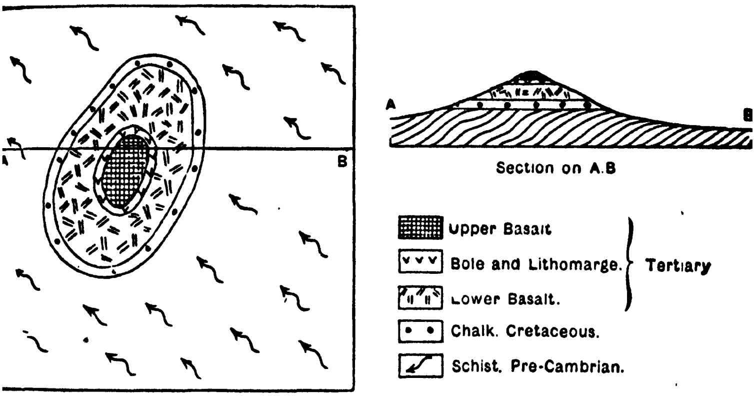


FIG. 37.

are preserved owing to the fact that they lie in hollows in the Chalk of the North Downs (quarter-inch map, Sheets 20–24).

In these cases the junction is, of course, an unconformable one, and the hollows have been produced in most instances, though not in the case of the Lenham Beds, before the formation of the newer rock.

Inliers.—The term *inlier* is used to designate an outcrop of an older rock surrounded by those of newer sediments.

These are not so common in unfaulted areas as are outliers, but they are sometimes produced along the courses of streams during the denudation of an anticline. Thus where a valley crosses an anticline, a patch of the

older rock in the core of the fold may be exposed in the bed of the stream, and an inlier be formed (Fig. 38).

Another type is produced where streams gash the flanks of an anticline, as in the case of the Cleveland Hills in North Yorkshire, where numerous streams have pro-

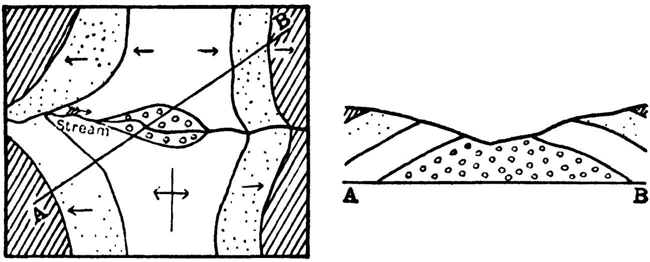


FIG. 38.—An Inlier in Conformable Strata.

duced inliers in this way (quarter-inch map, Sheet 4, and 1-inch map, Sheet 43).

Inliers may also be formed during the denudation of rocks affected by a qua-qua-versal dip, by the removal of the top of the dome (see p. 31).

Inliers of the above types may occur in either conformable or unconformable strata, but another class, of

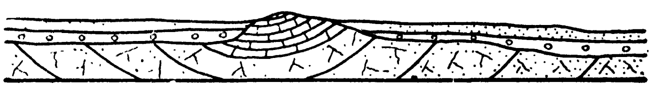


FIG. 39.—An Inlier in Unconformable Series.

which good examples are to be seen in the neighbourhood of the coalfields of Bristol and South Wales, and in many other parts of England, are dependent on the occurrence of unconformities. They are due to the presence of a hill on the surface of the older series, which has not been completely buried by the newer sediments, or if it has been covered is now revealed by the removal of the upper layers (Fig. 39).

In the bed of the Ballyemon River in County Antrim

an inlier is produced in the following manner: At the head of the valley the Trias, Chalk, and overlying Basalt dip up stream, and consequently their outcrops are V-shaped, the apex of the V pointing up stream. These beds rest unconformably upon pre-Cambrian Schists and Old Red Sandstone, the latter dipping down stream at an angle greater than that of the slope of the stream course. In consequence of this the outcrop of the Old Red Sandstone is also V-shaped, but the narrow end of the V points down stream, and an inlier of the Schist occurs between the two Vs, as illustrated in Fig. 40.

Outliers and inliers produced by faults will be discussed in Chapter V.

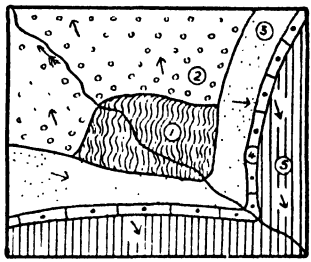


FIG. 40.—Inlier in Glen Ballyemon, Co. Antrim. (1) Schist; (2) Old Red Sandstone; (3) Trias; (4) Cretaceous; (5) Tertiary Basalt.

Decussating Folds.—Regions of folded strata are sometimes affected by later folds striking in a different direction, and in this way extremely complex outcrops are sometimes produced. These vary so widely in form that no general discussion of them is possible, but it may be well to remember that, where two anticlines cross, a dome-like structure with qua-qua-versal dip will be produced, while the intersection of two synclines gives rise to a basin.

It will be readily understood that symmetrical domes and basins produced in this manner are extremely rare in nature, as folded areas offer great resistance to subsequent plication in another direction, the result being that fractures usually occur. This resistance may be illustrated by an attempt to bend a piece of corrugated iron at right angles to the corrugations.

It frequently happens that folded areas are tilted by subsequent movements, and the outcrops resulting from

the denudation of such tilted or "pitching" folds are usually curved in the manner to be seen in Fig. 41.

The various complicated forms of outcrop which may arise in this manner may be illustrated by cutting sections of a piece of wood, showing rings of growth, in various directions, and are often well seen in polished pitch-pine desks and the like, where the table-surface represents the outcrops on the map and the ends of the desk show the strata in section.

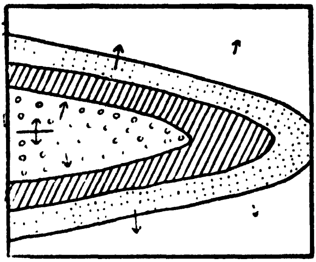


FIG. 41.—Outcrop of a Tilted Anticline.

Repetition of Folding.—It has been frequently observed that when folding has once taken place along an axis, there is a tendency for subsequent movements to take the same line, and these successive movements may take place in the same or in widely separated geological periods. Should denudation have taken place in the interval between successive movements of the fold, complicated and instructive varieties of unconformity are produced.

A good example of repetition of folding along the same line is exhibited by the great anticline of the Weald, which can be shown to have moved in pre-Cretaceous, post-Cretaceous and pre-Eocene, post-Eocene and pre-Pliocene, and finally in post-Pliocene times.

The more complicated case in which folding along a second axis has intervened between the first and second movements of a primary fold is well illustrated by a case from the South of Ireland (Geological Survey of Ireland, 1-inch map, Sheet 156; see also Fig. 42).

Here in the neighbourhood of Callan is an exposure of Silurian rocks forming an inlier; these are covered unconformably by the Old Red Sandstone, which is followed by the Carboniferous series. The Silurian rocks

were strongly folded along a north-east to south-west line (Caledonian), being thrown into a series of steep anticlines and synclines, before the deposition of the Old Red Sandstone, which is unaffected by this series of movements. Then followed the deposition of the Carboniferous rocks

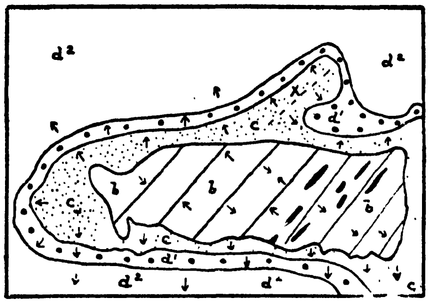


FIG. 42.—*b*, Silurian; *c*, Old Red Sandstone; d^1 and d^2, Carboniferous Rocks.

and a subsequent folding along an east and west line (Armorican), the Silurian inlier occurring in an anticline of this series. There then followed a minor movement along the original Caledonian axis, the evidence for which is to be seen on the map in the forms of the outcrops north of Ninemilehouse (X in Fig. 42).

CHAPTER V

DISLOCATIONS

DISLOCATIONS resulting from crustal movements are of frequent occurrence, and may be divided into normal faults, reversed faults, and thrust-planes and flaws, as described in Chapter II. Other dislocations of a more superficial character, but which sometimes produce results at the surface which are difficult to distinguish from those produced by faults, are known as land-slips. They are due not to crustal movements, but to denudation and the consequent slipping of blocks of strata towards a sea cliff or other free edge.

Normal Faults.—Fig. 43 is a section across a normal fault in horizontal strata, and will serve to illustrate the meaning of the terms applied to its various parts.

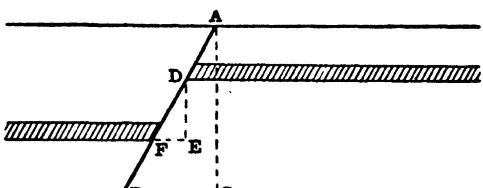


FIG. 43.—Section of a Normal Fault in Horizontal Strata

The *fault-plane* (AB in Fig. 43), that is, the plane along which the movement has taken place, is usually inclined, but does not depart widely from the vertical in the great majority of cases. The angle which the fault-plane makes with the vertical plane is called the *hade* of the fault, and is represented in the diagram by the angle

BAC, and is in all normal faults towards the downthrow side.

The term "downthrow" is applied to that side of a fault on which the strata are displaced downwards relatively to those on the other side, and the amount of displacement, measured vertically, is known as the *throw* of the fault (DE in the figure).

It will also be noticed that the fault in the diagram produces a lateral shifting of the strata as an effect of the hade. Thus the shaded bed is moved horizontally a distance equal to EF, and this is called the *heave* of the fault.

In most faults the fault-plane is more or less curved, and in consequence the hade, and therefore also the heave, is variable, and in cases of extreme curvature the rocks in the neighbourhood are much broken up, and a *fault-breccia* or *fault-rock* is produced.

On most geological maps the presence of a fault is indicated by some special type of line, which distinguishes its outcrop from those of bedding-planes. Thus in the 1-inch maps of the Geological Survey of the United Kingdom faults are represented by white lines upon the coloured surface, or in the case of a few of the more recent colour-printed maps by dark blue lines. In many instances the downthrow side of a fault is indicated by a distinguishing mark, as in Figs. 44, 49, and 62, and the amount of the throw may also be given.

In the absence of any special indication, the existence of a faulted boundary may be inferred from a variety of evidence, as, for example, a sudden change in the direction of dip and strike, the absence from the sequence of strata present in contiguous areas, the duplication of outcrops, the displacement of lines of outcrop, and the sudden ending of folds or of other faults.

The fact of the existence of a fault having been determined from the map, it then remains to ascertain the direction of its throw, the amount of throw, and, if possible, the hade.

The determination of the downthrow side of a fault is usually attended with but little difficulty, even where the distinguishing mark is omitted. The general rule is, that that side of the fault on which occurs the outcrop of the newest rock is the downthrow side, and though at the point where a given line of section crosses the fault the same rock may be found on both sides, the necessary information may usually be obtained by following the fault along its outcrop until a point is reached where the rocks on its two sides are unlike.

It must be stated in this connection that faults sometimes change their direction of throw, as will presently be described; this phenomenon, however, occurs in but a small percentage of cases.

When the fault is a short one, and is confined to the outcrop of a single rock, it is sometimes impossible to determine the downthrow side, unless the distinguishing mark is attached; and in cases of this kind the position of the fault should be indicated in the section by a vertical line.

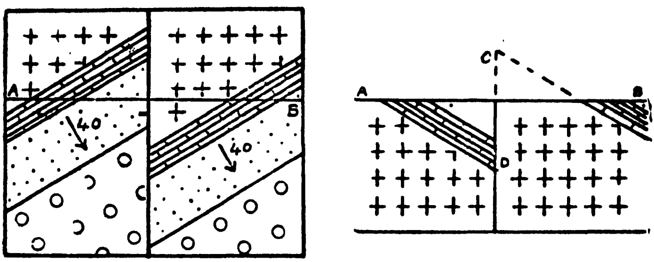
The determination of the amount of throw is a much more difficult matter, indeed it is only in a few cases that this can be done with accuracy when dealing with maps up to and including the scale of 1 inch to a mile; but an approximation may be obtained graphically in the process of drawing the section if this be done to true scale and due care be taken to ensure the correctness of the angle of dip.

Thus, in Fig. 44*a* are represented in plan the outcrops of several beds of rock, intersected by a fault. From the dip arrows it will be noted that the bed marked with circles is the newest, while that with crosses is the oldest. We may now proceed to draw a section along the line AB, and for the sake of simplicity the surface of the ground will be assumed to be horizontal (Fig. 44*b*). Now at the point where the line AB crosses the outcrop of the fault the dotted bed is thrown against that marked with crosses, which is older. Applying the principle that the newer rock

is on the downthrow side, we find that the downthrow is towards A.

It is assumed here, for reasons which will presently appear, that the fault possesses no hade, *i.e.* the fault-plane is vertical. It will also be necessary to find the amount of apparent dip along AB, as this will obviously be less than 40°, which is the true dip in the direction of the arrows. This may be obtained from the table on pp. 128, 129, the use of which will be explained later.

The positions of the various outcrops having been marked off to scale along AB (Fig. 44*b*), the strata can now be inserted, dipping at the appropriate angle, and the



(*a*) (*b*)

FIG. 44.—Plan and Section of a Normal Fault.

section will be complete. On adding the parts removed by denudation, as indicated by the dotted lines, the amount of throw may be measured, being obviously equal to CD in the section.

The above method is the one which will be found most useful in dealing with the fault-problems which occur in the course of map-reading, but it is desirable to discuss the matter more fully in view of mining and engineering problems which may arise.

It will be seen from Fig. 44*a* that one effect of the fault has been a lateral shifting of the outcrops, and the amount of this lateral shift is dependent upon three factors, namely: (1) the throw of the fault; (2) the dip of the strata; (3) the hade of the fault.

In practice the problem which usually presents itself is the determination of the amount of throw, and although the amount of displacement is easily measured and the dip of the strata is given on the map, an accurate determination of the throw is often impossible owing to lack of information regarding the hade.

Owing to the fact that the hade of a fault varies from place to place, both vertically and horizontally, its amount is not usually indicated on geological maps, and in drawing sections it is usual to assume a small hade (say 10°) towards the downthrow side.

When the hade is nil, or when the fault runs accurately in the direction of the dip, the hade will have no effect upon the displacement of the outcrop; but the effect comes in and rapidly increases as the fault swings round to the direction of strike, or as the fault-plane leaves the vertical.

In order to illustrate the relation of displacement of outcrop to throw, we will first consider the case in which the fault runs accurately in the direction of dip, as in this case the hade will have no effect. The rule here enunciated will be found to be approximately true also in the case of all *dip-faults*, that is, those running actually or approximately in the direction of the dip.

The throw may be determined in the case proposed by multiplying the horizontal displacement of the outcrop, that is, the displacement shown on the map, by the tangent of the angle of dip, or it may be ascertained graphically by the method employed on p. 52 for the determination of the vertical depth of a stratum, namely by drawing an angle (ABC in Fig. 27) equal to the angle of dip, marking off a distance Bx equal to the horizontal displacement, and measuring the length of the perpendicular xy. The distance xy will represent the throw of the fault, for $xy = Bx \tan ABC$.

In the case of a fault running obliquely to the direction of dip, it will first be necessary to ascertain the angle of apparent dip in the direction of the fault, which can be done by one of the methods described in Chapter VIII., or by means

of the table on pp. 128, 129, and then to multiply the displacement of the outcrop along the line of fault by the tangent of this angle. Thus, in Fig. 45 the fault runs at an angle of 45° to the direction of dip, the amount of which is 30°; and the displacement along the line of the fault is 100 feet. The angle of dip in the direction of the fault is 22° 12′ from the table on p. 128; and the throw, which is, of course, towards the west, will therefore be $100 \times \tan 22° \ 12' = 100 \times \cdot 408 = 40 \cdot 8$ feet. A similar result would be obtained by measuring the displacement in the direction of the dip, *ac* in the figure, and multiplying this by tan 30°; $ac = 70 \cdot 7$ feet, and $ac \tan 30° = 70 \cdot 7 \times \cdot 577 = 40 \cdot 79$ feet.

Should the points *a* and *b* in the figure be at different levels, the amount of this difference must be added to or subtracted from the result obtained as above.

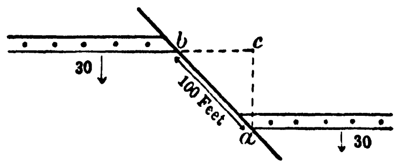


Fig. 45.

An approximation to the actual throw of a fault may be obtained from a consideration of the stratigraphical position of the rocks on its two sides. In order that this may be done, it is necessary to know the local thickness and stratigraphical arrangement of the rocks; thus if it be known that the thickness of the rocks which lie between the strata on opposide sides of the fault is 1000 feet, it may be assumed that the throw is of this order of magnitude, but of course the dip of the strata and the hade and direction of the fault must be taken into account if a correct value is required.

Thus, take the case of a fault having a hade of 15° and cutting beds whose dip in a direction at right angles to the line of the fault is 30°, and let it be assumed that the rocks brought into juxtaposition by the fault are separated by 1000 feet of strata; then the throw may be ascertained as follows by means of a scale drawing (Fig. 46).

Draw a vertical line AB, and at A make an angle BAC

equal to the hade (15°), then AC will represent the inclination of the fault-plane. On AC take any point D, and through D draw a horizontal line EDF; at D make the angle FDG equal to the dip (30°), and at right angles to GD draw DH equal to the stratigraphical throw (1000 feet), and through H draw HK parallel to GD, meeting AC in K. Finally, through K draw a horizontal line, and from D let fall a perpendicular to this, meeting it in L. Then DL will represent the throw of the fault.

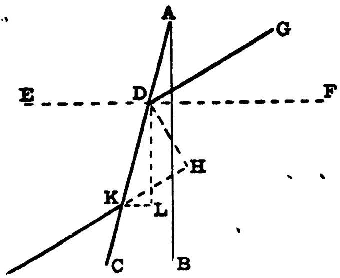


FIG. 46.

Faults are classified as *dip-faults* and *strike-faults* according to their direction, and in the case of the latter the effect upon the outcrops is to alter their width, or in cases of greater movement to conceal or duplicate them according as the throw is with or against the dip. In strike-faults the hade will have its maximum effect in

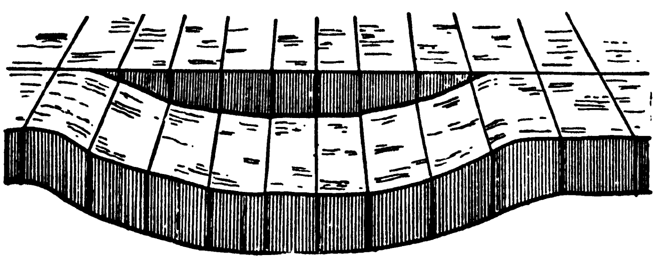


FIG. 47.

modifying the outcrops, and must therefore be taken into account in all cases where the throw is to be calculated from the dip and displacement.

In some faults the throw varies from place to place, and may die out entirely in one or in both directions. The manner in which this is brought about will be understood on reference to the diagram (Fig. 47).

Again, in travelling along a fault, it may be found that the throw gradually diminishes to zero, and is then replaced by a downthrow towards the opposite side, which increases as the neutral point is left behind, as illustrated in Fig. 48.

Another way in which variation in the amount of throw

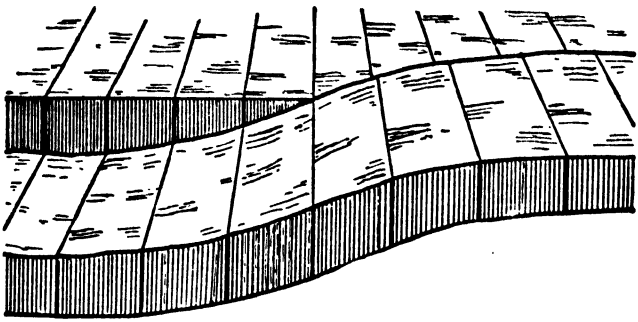


FIG. 48.

may be brought about is by the intervention of other faults. Thus, in the plan (Fig. 49), in which the throws of the various faults are indicated in feet, and the figures in each case printed on the downthrow side, the throw of the main fault *ab* is only 30 feet at *a*, but the cross-fault,

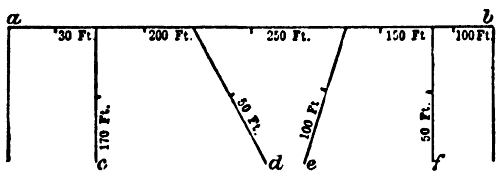


FIG. 49.

c, with its downthrow of 170 feet, increases this to 200 feet, which is still further modified by the throws of *d*, *e*, and *f*.

A series of parallel faults may all throw in the same direction, thus producing *step-faults*, as in Fig. 50, or they may fall in opposite directions, giving an arrangement similar to that of a syncline, and known as a *trough-fault* (Fig. 51). *Ridge-faults* as in Fig. 52 also occur.

When a fault traverses more than one geological formation, the throw of the lower group of rocks may be considerably greater than that of the upper series. This is due to repetition of faulting along the same line of fracture. Thus in Fig. 53, which is a section of such a fault, the first movement took place after the formation of the Coal Measures, and amounted to some 970 feet. This

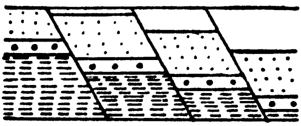


FIG. 50.—Section of Step-faults.

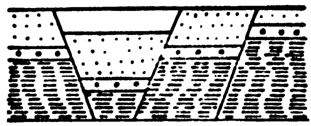


FIG. 51.—Section of Trough-faults.

was accompanied or followed by the reduction of the surface of the land to a level by atmospheric agencies and the subsequent deposition of the Permian rocks. After the Permians were formed a further movement of 30 feet took place, which affected the Permian and Carboniferous rocks equally. The Permian rocks, being, of course, un-

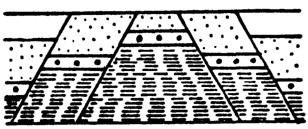


FIG. 52.—Section of Ridge-faults.

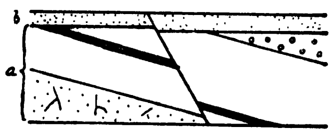


FIG. 53.—Section of Fault, showing evidence of Movement at two distinct periods: (*a*) Coal Measures, (*b*) Permian.

affected by the earlier movement, show a displacement of only 30 feet, while the underlying Coal Measures are thrown 30 + 970, that is to say, 1000 feet. This case is by no means exceptional, many faults being known to have moved in two, and in some cases in more than two, geological periods.

Owing to the variability of the hade of faults, no record of its amount is put upon geological maps, but in some cases it may be obtained approximately from the informa-

tion given on the 6-inch maps of the Geological Survey. On these maps the position of the underground intersection of a seam of coal with a fault-plane is indicated by a yellow line vertically above the intersection, the depth being also given (Fig. 54). On drawing a section to scale, the hade is of course obtained.

Reversed Faults.—Reversed faults are of much less frequent occurrence than those above described. They are due to lateral compression of the crust rather than to mere subsidence under the action of gravity.

They differ from normal faults in that the hade is towards the upthrow side, and is usually a large angle.

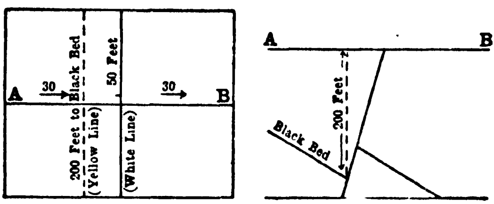


FIG. 54.

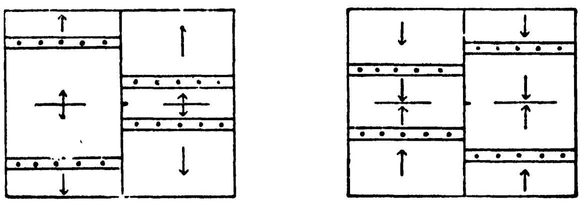
Under these circumstances it will be realised that the effect of the hade upon the displacement of the outcrops is much greater than it is in the case of normal faults, and that unless the hade is known it is not possible to determine the throw with accuracy, though some idea of its magnitude may be gathered from the stratigraphical throw, where the thickness of the beds involved is known.

Reversed faults form a link between normal faults and thrust-planes, to which latter group they really belong, and they only differ from typical thrust-planes in hade and the proportion of vertical to horizontal movement. The presence of a fracture of this type is usually indicated upon geological maps by printing the words "reversed fault" along the outcrop, the direction of throw being indicated as in the case of normal faults.

Forms of Outcrop in Faulted Areas.—The effects of a normal dip-fault in dislocating the outcrops of the strata has already been considered in the case illustrated in Fig. 44, where it was assumed that the dip was constant and in the same direction on both sides of the fault.

Where the amount of dip varies, as in folded areas, or where the district is affected by a number of faults with varying amounts of throw, the outcrops suffer considerable modification.

If a dip-fault traverses a series of rocks whose dip gradually diminishes, say, from north to south, the amount of displacement of the outcrops will be found to increase in the same direction provided that the throw



(*a*) (*b*)

FIG. 55.—(*a*) Plan of Fault crossing Anticline ; (*b*) Plan of Fault crossing Syncline.

remains constant, and should the direction of dip be reversed, as in the case of an anticline or a syncline, the direction of the displacement of the outcrops will also be changed.

In the diagrams Fig. 55 *a* and *b* the effect of a dip-fault upon the outcrops in anticlinal and synclinal areas is illustrated, and it will be seen that in the anticline the outcrops are brought nearer together on the downthrow side, while the reverse is the case with the syncline.

In the case of vertical beds intersected by a fault there is of course no dislocation of the outcrops, except such as may be due to the hade and consequent heave of the fault, and in the case of highly inclined beds the displacement is small.

This applies equally to the case of one normal fault

which is cut by a second one, for since the fault-plane is nearly vertical its outcrop will be but little displaced.

Strike-faults produce in some instances very marked results upon the outcrops, but when they continue in the same bed, run accurately along the line of strike, and have but little throw, they produce no apparent displacement.

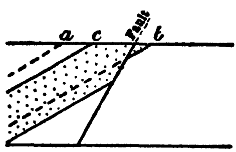


FIG. 56*a*.—Section of Strike-fault showing Narrowing of Outcrop.

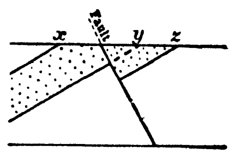


FIG. 56*b*.—Section of Strike-fault showing Widening of Outcrop.

The effects of these small strike-faults on the outcrops will be first considered, and can best be detected by comparing the width of the outcrop in which they occur with that of the same rock where unfaulted. It will be found that the faulted outcrop is wider or narrower than

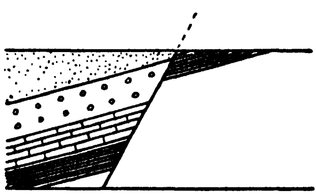


FIG. 57*a*. — Section of Strike-fault showing Concealment of Outcrops.

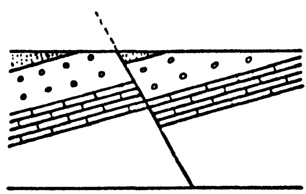


FIG. 57*b*.—Section of Strike-fault showing Duplication of Outcrops.

the normal one according to the direction of throw of the fault.

Take first the case where the downthrow is in the same direction as the dip (Fig. 56*a*).

Here the width of the unfaulted outcrop would be *ab*, but owing to the downthrow it is narrowed by the amount *ac*.

Fig. 56*b* illustrates a throw in the opposite direction,

and it will be seen that the outcrop is widened by the amount *yz*.

With a greater throw the outcrops may be concealed or duplicated as seen in Fig. 57 *a* and *b*.

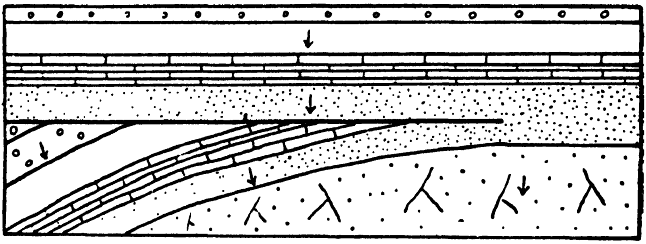


FIG. 58.—Plan of Outcrops in the Neighbourhood of a Strike-fault with Diminishing Throw.

In the case of a strike-fault with a diminishing throw, the outcrops may appear as in Fig. 58, an arrangement which at first sight suggests an unconformity, but on closer inspection proves to be due to repetition of beds by the fault.

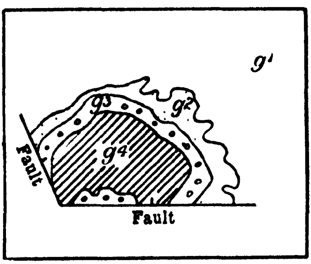


FIG. 59.—Plan of Bredon Hill, a Faulted Outlier. g^1, Lower Lias; g^2, Middle Lias; g^3, Upper Lias; g^4, Inferior Oolite.

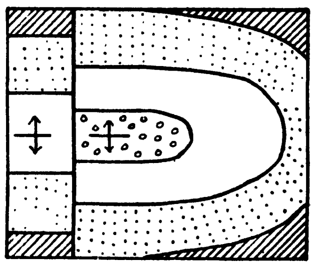


FIG. 60.—A Faulted Inlier.

Outliers and Inliers produced by Faulting.—Outliers are in some instances due to faulting, as for example Bredon Hill, between Tewkesbury and Evesham. (Fig. 59, quarter-inch map, Sheet 15.)

Faulted inliers are much more common than the unfaulted type described on pp. 61–63, and may be produced in a variety of ways.

They may be due to intersecting faults, as is the inlier of Carboniferous Limestone surrounded by Millstone Grit, which occurs in Nidderdale above Pateley Bridge (1-inch map, Sheet 51), or to a single fault cutting across the outcrop of folded strata (Fig. 60).

Thrust-Planes and Flaws.—Thrust-planes are usually indicated by lettering upon the maps, and may or may

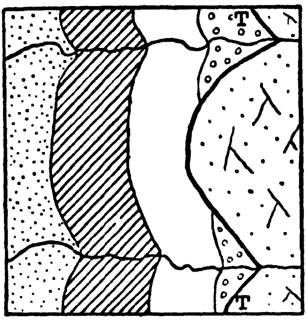


FIG. 61.—Outcrop of a Thrust Plane, TT

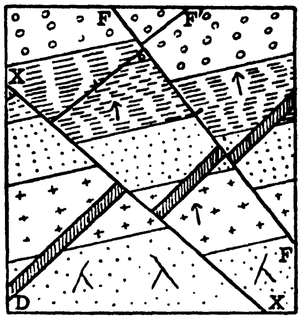


FIG. 62.—Plan showing Effect of a Normal Fault, FF, and of a Flaw, XX, upon the Outcrops of Planes of various Degrees of Dip.

not be indicated by white lines. Their outcrops are, on account of their large hade, much more complicated than those of normal faults, and resemble rather the boundaries of stratified rocks.

In general appearance in plan thrust-planes strongly resemble unconformities (Fig. 61), from which, however, they can in most instances be distinguished by a study of the relationship of the strata in their vicinity. For example, the rock which occurs above a thrust-plane may be either older or belonging to the same group of rocks as that below it, which is of course impossible in the case of an unconformity.

Flaws, being more or less vertical fractures, usually outcrop as comparatively straight lines, and in this they resemble normal faults, with which they are readily confused on a casual examination of a map.

Being due to horizontal movements, they will, unlike normal faults, displace all outcrops which they cut to the same extent, independently of the amount of dip possessed by the strata. Thus a flaw crossing gently-inclined strata penetrated by dykes and cut by normal faults of older date, will displace all the outcrops to the same extent. This will be seen on an inspection of Fig. 62, in which XX is the outcrop of a flaw, FF and F′ those of normal faults, and D that of a dyke. It will be noticed that the dyke owing to its nearly vertical position is shifted but little by the normal fault, while it shares equally with the surrounding strata the displacement due to the flaw.

Landslips.—Landslips, as has been explained on p. 66, are surface features due to denudation, and are usually

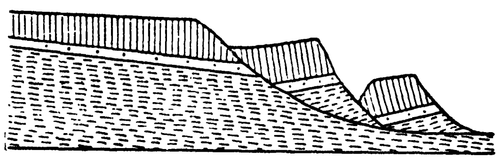


FIG. 63.—Section of Landslips.

indicated by the word "landslip," or merely "slip," upon geological maps. On some of the 1-inch maps of the Geological Survey of Ireland they are indicated by lines of round white dots. They cannot be accurately represented in section from the information given in the map, but may be indicated conventionally as in Fig. 63.

CHAPTER VI

IGNEOUS AND METAMORPHIC ROCKS IN PLAN AND SECTION

IGNEOUS rocks are usually represented by stronger colours, deep reds, greens, and purples, than are used for sedimentary deposits, and therefore form conspicuous features on the maps of districts in which they occur.

For our present purpose it is not so necessary to consider the petrological character of igneous rocks, as their mode of occurrence and their relations to the surrounding rocks, with a view to the determination of their geological age. Igneous rocks may for this purpose be placed in two categories, contemporaneous and intrusive.

Contemporaneous Igneous Rocks.—This group includes all the volcanic rocks, or those which have been formed upon the surface of the earth, or poured out over the floor of the sea during submarine eruptions. They comprise lava flows, beds of volcanic ash, scoriæ, lapilli, and other fragmentary materials blown from volcanic vents by the explosions of the escaping steam.

The term contemporaneous is applied to them as indicating that they were formed during the same geological period as the normal sediments with which they are associated, and it will be found that they differ in their mode of occurrence from ordinary stratified rocks only in the fact that their bedding is less regular, their thickness less constant, and their lateral extension more circumscribed.

Lava Flows.—Lava flows from a volcano of the Vesuvian type usually only extend for short distances

from their point of origin, are of small width, and vary rapidly in thickness; but another type of flow, that which originates from fissures, may cover a very wide area, and owing to the greater fluidity of the basic lavas, of which these flows usually consist, may be much more regular as regards the thickness of the sheets.

Outcrops of contemporaneous lavas are to be seen in Fig. 42, where they occur in the Silurian rocks, and it will be noticed that their outcrops, though less regular than those of normal sediments, follow the general lines of strike of the formation in which they occur.

Beds of consolidated volcanic ash or tuff conform to the ordinary laws of sedimentary rocks, but are more limited in extent and more variable in thickness. They may rest conformably or unconformably on the rocks beneath them, and may or may not be associated with lavas.

Thus the presence of contemporaneous igneous rocks does not greatly complicate the problems of map-reading, their outcrops being capable of interpretation on the same general lines as those adopted in the case of other stratified deposits.

Intrusive Igneous Rocks.—Intrusive igneous rocks occur in a variety of forms determined by the conditions of intrusion. They differ from contemporaneous rocks in the fact that their outcrops cut across those of the associated sediments, except in the case of certain "sills," presently to be described.

The following are the principal types of intrusion:—

Batholites.—This term is applied to large more or less dome-shaped masses of igneous rock of coarsely crystalline texture, such as granite, syenite, and gabbro, which have solidified at considerable depths within the earth's crust, and have been subsequently laid bare by denudation. In some instances they are probably the solidified subterranean reservoirs which supplied some long-extinct

volcano, of which all other traces have been removed, but there are also some bosses of this type which, so far as can be ascertained, do not appear to have given rise to any surface manifestations.

Usually the edges of the surrounding strata are not displaced, but are sharply cut off by the intrusive rock, as though it had reached its present position by melting and absorption.

In other cases the intrusion has pushed aside the surrounding materials, and the effect of this can be readily detected in the distortion of the strata and consequent disturbances of dip and strike. When the disturbance of the surrounding strata is great the intrusion

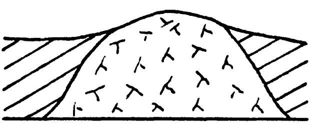


FIG. 64.—Section of Batholite.

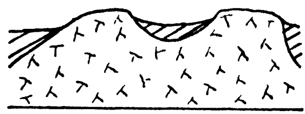


FIG. 65.—Section of Batholite.

may perhaps be more correctly described as a laccolite (see page 84).

The form of the upper surface of batholites is very varied. They may be simple domes with steeply inclined sides, and appear in section as in Fig. 64, or they may be extremely irregular in form, and appear at the surface as a number of small bosses which are connected by the general mass of the intrusion at no great depth below the surface (Fig. 65).

Again the outlines both in plan and section may be extremely irregular, the main mass sending off tongues and branches into the surrounding rocks (Fig. 66, *a* and *b*).

It is frequently very difficult or even impossible to ascertain the underground form of a batholite, and we cannot therefore expect much information on this point in a map, except in cases where mining operations have been carried on along the margin, the form of which is consequently known.

The intrusion of an igneous rock often produces chemical and mineralogical changes in the neighbouring rocks, and where these alterations are sufficiently great to produce appearances which are recognisable in the field, the zone or aureole of *contact metamorphism* has been mapped.

The size and form of the aureole of metamorphosed rocks may give valuable information as to the subterranean form and extent of the intrusion; thus in the case of the granite near Falmouth in Cornwall (see 1-inch map, Sheet 352) the aureole is narrow, from which it may be concluded that the surface of the granite is steeply inclined, while on the northern side of the same intrusion in the

a *b*

FIG. 66.—Plan and Section of an Irregular Batholite.

neighbourhood of Redruth the aureole is very well marked and of great extent, pointing to a wide subterranean extension of the granite at no great depth below the surface, which is confirmed by the occurrence of two detached exposures.

Laccolites.—This type of intrusion is closely akin to the batholite, and when of large extent is with difficulty distinguished from it.

Laccolite is the name which has been given to a lenticular mass of igneous rock injected amongst sedimentary strata in such a manner as to force them into a dome-like form; an injected blister as it were. The strata along the top of such a dome are usually fractured, and frequently injected by tongues of the igneous rock.

Laccolites may be either horizontal as in Fig. 67, or inclined as in Fig. 68, owing to tilting subsequent to their injection.

There is no conventional sign used in British geological maps to differentiate batholites from laccolites, and they

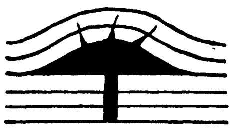


FIG. 67.—Section of Laccolite.

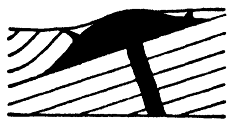


FIG. 68.—Section of Laccolite.

cannot be readily distinguished by the forms of their outcrops.

Sills or Intrusive Sheets.—The typical intrusive sill is of great lateral extent in comparison to its thickness, which is usually fairly constant, thus distinguishing it from the laccolite.

When sills occur in sedimentary strata they usually follow the bedding planes, and thus resemble lava flows. The sills are, however, usually wider in extent and more regular as regards their thickness than are lava streams.

In some instances sills branch and in others change

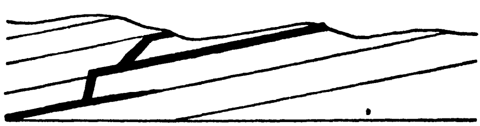


FIG. 69.—Section of an Intrusive Sheet or Sill, showing Change of Horizon and Branching.

their geological horizon one or more times, as indicated in Fig. 69, and either of these phenomena, when present, serves to distinguish them from lava flows.

In the field it is possible to distinguish the sill by the fact that it metamorphoses both the rocks on which it

rests *and also those above it*, whereas the lava flow can, of course, only produce changes in the floor over which it flows, but unless the metamorphic rocks are indicated upon the map this means of identification is closed to us.

The above phenomena are well shown by the Great Whin Sill of the North of England, which is intrusive in the Carboniferous rocks of the Pennine Chain, and which changes its horizon by a number of steps amounting in all to nearly 1000 feet, while on Thistle Green and Widdybank Fell, saccharoid limestone, which is a product of contact metamorphism, is shown in contact with the upper surface of the sill, thus confirming its nature (1-inch map, Sheets 25 and 31).

Since sills conform generally to the planes of stratification, their outcrops will follow those of the sedimentary rocks of the district, except at points at which a change of horizon takes place, where they resemble in all respects those of the *dykes* next to be described.

In section sills will, of course, resemble ordinary strata in their mode of arrangement.

Dykes.—Dykes are more or less vertical sheets of igneous rock which have been injected into fissures in the crust, and which, therefore, frequently cut the planes of stratification at high angles. They are usually of no great breadth, but may extend over long distances. Owing to their approach to the vertical position, their outcrops will run across the map in nearly straight lines, and thus resemble those of faults or of highly inclined strata.

In section it is usual to indicate dykes by vertical red lines, no information being obtainable from the map as to their inclination.

Dykes may branch, and they sometimes connect with laccolites and intrusive sheets, or they may swell out into bosses, as in the case of the Bolam Dyke in Durham.

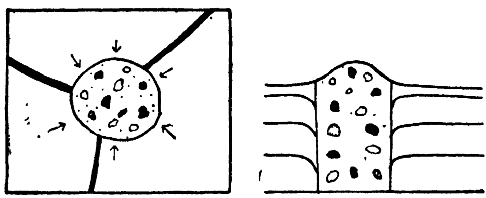
The outcrop of a dyke may be interrupted in several ways. The dyke may fail to reach the surface in certain

places, or it may be partially covered unconformably by later sedimentary accumulations. Occasionally the outcrop of a dyke consists of a series of long narrow exposures arranged in échelon, owing to a splitting and bifurcation of its upper parts.

Dykes often occur in parallel groups, as in Skye and Antrim, or they may radiate from a centre of volcanic activity.

Necks or Pipes.—These are the filled-up conduits of volcanoes now extinct. They may consist of solidified lava or of volcanic agglomerate and tuff.

Owing to the superior hardness of their rocks, they



a *b*

FIG. 70.—Plan and Section of a Volcanic Neck.

usually form hills, which are often isolated and conical or dome-shaped, forming striking features in the landscape. Their outcrops are usually circular or elliptical in form, but they may be irregular, and are frequently cut by dykes or have a series of dykes radiating from them.

The strata through which these necks have been drilled may show a dip inwards towards the centre, as in Fig. 70, *a* and *b*.

Necks are sometimes associated with other distinct traces of volcanic activity, such as beds of ash and lava flows, but they may be, and often are, the sole remaining traces of former volcanicity.

The Geological Age of Igneous Rocks.—Contemporaneous igneous rocks are, as their name implies, of the same geological age as the rocks with which they are

associated, but in the case of intrusive rocks a difficulty sometimes arises in the determination of the geological period of their origin.

In this connection the first thing to bear in mind is that the intrusive rock is newer than the rocks in which it is intruded. It does not follow from this, however, that the intrusion belongs to a later geological period, as it may have been produced merely at a later stage of the same period.

In cases of unconformity it can sometimes be shown that dykes and other intrusions cut the lower formation and are unconformably overlaid by the newer, in which case the age of the intrusion is obviously intermediate. Useful information on this subject may frequently be obtained by studying the relation of intrusions to faults whose geological age can sometimes be determined.

Again, a study of the relation of one set of intrusions to another may often lead to the determination of the age of an igneous rock.

As an example of the way in which information may be acquired by this method, the case of the granite of the Mourne Mountains in County Down, Ireland, is instructive. The granite penetrates the Silurian rocks of the district and produces a certain amount of contact metamorphism in them. From this it may be concluded that the granite is post-Silurian, and since it is covered unconformably by certain Pleistocene (glacial) deposits, it is obviously pre-Pleistocene (1-inch map, Sheet 60).

This is the direct evidence, and it leaves a very wide space of time in which the granite might have had its origin. Further information may, however, be obtained from a study of the relation of the granite to certain other intrusive rocks in the district.

The Silurian rocks of County Down are penetrated by very numerous basaltic dykes, which, from their general direction and petrological characters, are known to belong to the same period as the great basaltic lava-flows of the Antrim Plateau. Between the upper and lower series of

these lavas are certain beds which contain the remains of plants, and the study of these has shown them to be of Tertiary age. The Mourne granite can be seen in several sections to cut the dykes of this series, and is therefore obviously of a later date than they.

In this way, then, it is proved that the granite is of Tertiary age, and of later origin than the basalts of the plateau. Many other applications of this method of reasoning will suggest themselves, but the above will serve as an example.

Metamorphic Rocks.—These may for present purposes be divided into those due to contact metamorphism, as described on p. 84, and, consequently, confined to the immediate neighbourhood of igneous rocks, and those extending over wider areas and not directly connected with an intrusion, which are due to what is known as regional or dynamic metamorphism.

To this latter group belong the gneisses and crystalline schists which occupy large areas in the North-west Highlands of Scotland, in the North-west of Ireland, in Canada, and many other regions. They have in some cases resulted from the crushing of igneous rocks, in others from the compression and shearing of sediments, but so great have been the changes brought about, that the original character of the rock cannot in many instances be determined.

The planes of stratification are often completely obliterated, and new planes known as foliation planes and planes of schistosity have been produced.

In mapping rocks of this class the dip and strike of these planes are indicated by arrows, which are distinguished from the ordinary dip arrows by drawing them with a double shaft, or by some similar device, which will, of course, be indicated in the margin of the map. In drawing sections across areas of metamorphic rocks, the planes of schistosity, &c., will be treated as though they were planes of stratification, their form and inclination being determined in the same manner.

CHAPTER VII

GEOLOGICAL HISTORY FROM MAPS

By applying the methods of interpretation described in the foregoing chapters, it is often possible to determine with accuracy, and in some detail, the geological history of a district, and the connection existing between its geological structure and physical geography.

Practice in work of this kind is the most valuable exercise which can be undertaken by a student of geology, short of actual experience in the field. It should never be allowed to supersede field work, but it enables the beginner to become acquainted with the structure and history of many districts which it is impossible for him to visit, and will assist him more than any other part of his work in acquiring that "eye for a country" without which successful geology is impossible.

As the methods of interpretation have already been described, it only remains to indicate how the various pieces of information obtained from the map may be linked together to form a history of the district. This will best be accomplished by giving a few examples (Figs. 71–77), which are also intended to serve as diagram maps for purposes of practice. The student should attempt to draw his own sections before consulting those given, and to supplement these by others drawn in different directions.

The order of superposition of the strata is given in most cases, but this is unnecessary, as it can be deduced from the arrows.

Figure 71.

(1) *Order of Superposition of Beds.*

The oldest bed, *m*, occurs in the north-west corner of the area, and is again brought to the surface in the

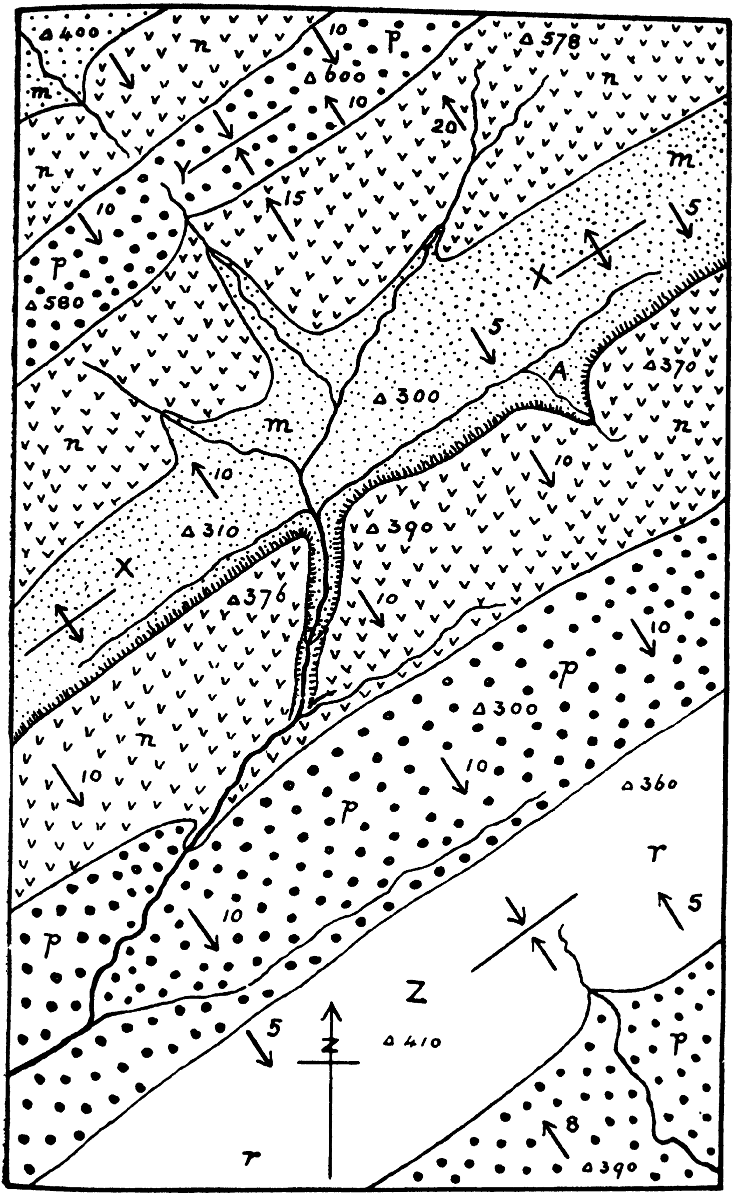


FIG. 71.
Scale 1 inch to the mile.

core of the anticline, which runs from north-east to south-west across the centre of the district. The other rocks exposed in ascending order are *n*, *p*, and *r*.

(2) *Folds.*

The country has been folded along a north-east to south-west axis, the anticline and synclines shown being of the symmetrical type, and forming a series of gentle undulations.

(3) *Physical Geography.*

The country has been considerably denuded subsequent to the movements, as the synclines form the high ground, while the central valley (X) occurs on the anticlinal axis.

The two synclines at Y and Z form the principal watersheds of the district.

The large river rises near the centre of the synclinal area Y and flows into the anticlinal valley X, where it receives several tributaries. It then cuts through the escarpment formed by the bed *n*, forming a gorge, and later is joined by two subsequent tributaries.

A good example of an obsequent stream is seen at A.

Figures 72 and 73.

(1) *Order of Superposition of Beds.*

The order of superposition of the beds of rock forming the area is *a*, *b*, *c*, *d*, *e*, *f*, and between *e* and the beds below it there is an unconformity, as can be seen from the fact that *e* rests successively from south to north upon *b*, *c*, and *d*.

(2) *Escarpment, Outliers, and Inlier.*

The series *e*, *f* forms an escarpment along the eastern edge of the map, and there is an outlier of *e*, resting unconformably upon *c* and *d*, in the northern portion, and one of *f*, resting conformably on *e*, near the centre. In the southern part of the map the streams have breached the crest of an anticline and

exposed an inlier of the bed *a*, the oldest in the district.

The marked transgression of the bed *e* over the members of the older series shows that there was prolonged denudation subsequent to the folding and prior to the deposition of *e*.

Figures 74 and 75.

The oldest rocks in the area are the Archæan, which have suffered considerable folding, but have a prevalent dip towards the south-east.

The Old Red Sandstone rests unconformably upon the Archæan on its north-western side, as indicated by the difference in the direction of dip of the two formations. It is followed by the Carboniferous rocks, which both here and in the southern part of the area rest conformably upon it. They consist in ascending order of the Carboniferous Limestone Series and the Millstone Grit.

These Old Red and Carboniferous rocks are thrown into a syncline in the southern part of the map, and are cut off to the north by the fault F1. The synclinal axis pitches slightly towards the south-east, causing the curved outcrop near the fault F1.

The Coal Measures appear to be absent from the area, as do also the Permian, Triassic, and Jurassic rocks, the next formation represented being the Cretaceous.

The chalk (*h*) rests unconformably upon the rocks beneath, being seen lying upon the pre-Cambrian, the Old Red and the Carboniferous rocks, and in the outlier in the north-west overlying the fault F2.

From a study of the dip arrows it will be seen that the Tertiary Basalt rests unconformably upon the Chalk and also overlaps it to the southward on to the Old Red Sandstone.

There is a mass of granite intrusive in the pre-

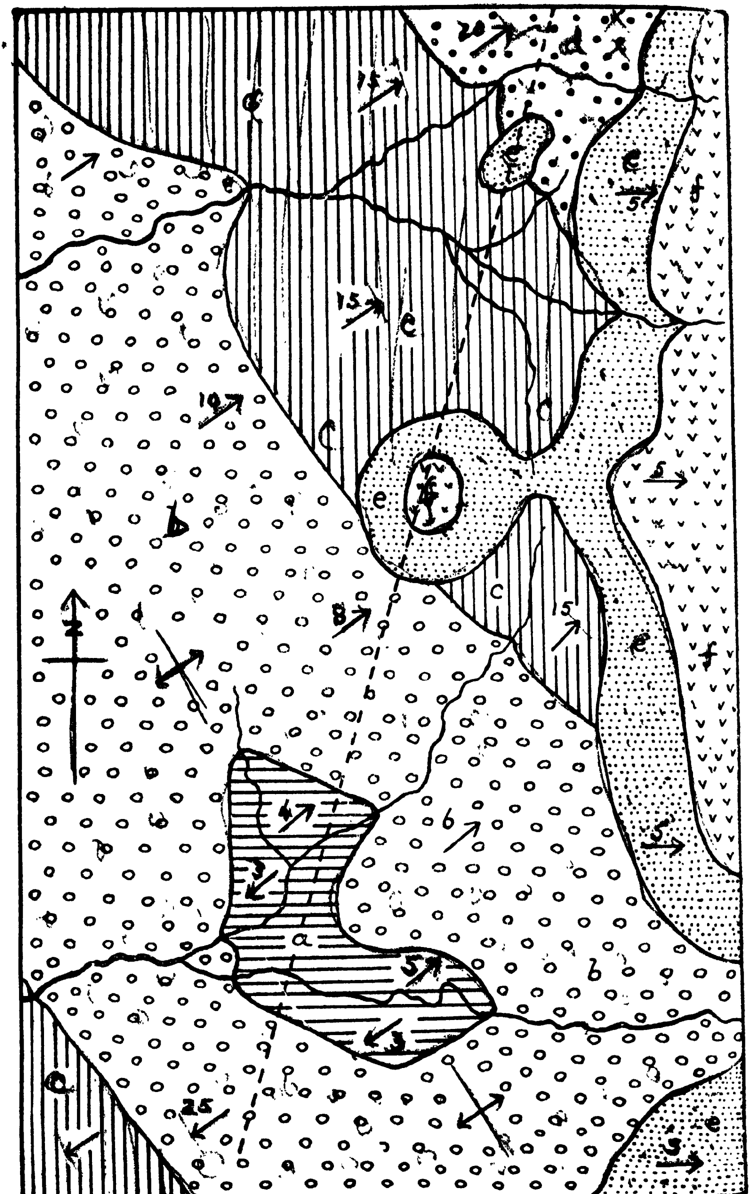


FIG. 72.
Scale 1 inch to the mile.

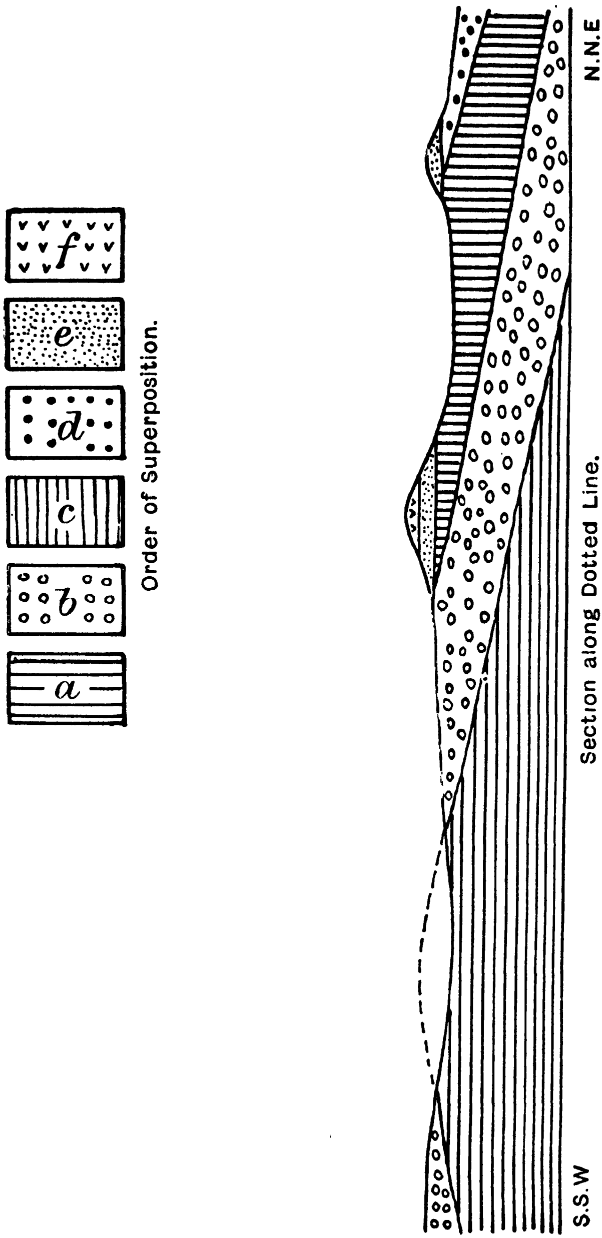


Fig. 73.

Scale 1 inch to the mile.

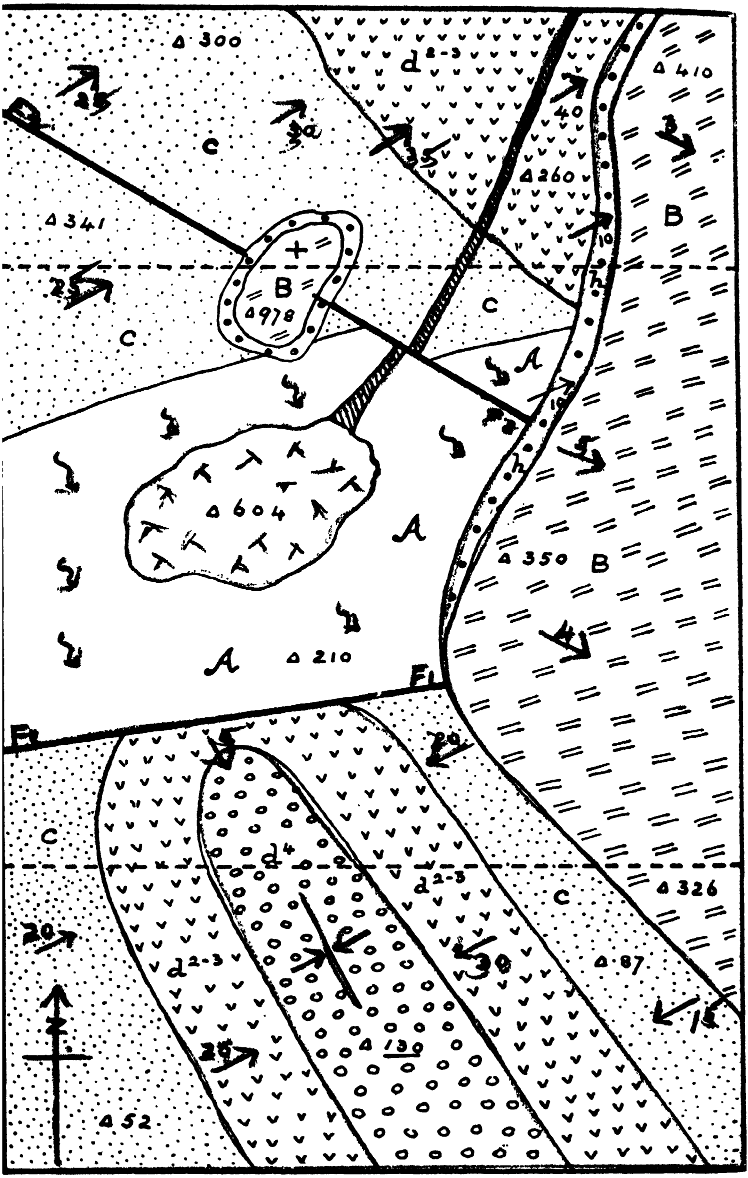


FIG. 74.
Scale 1 inch to the mile.

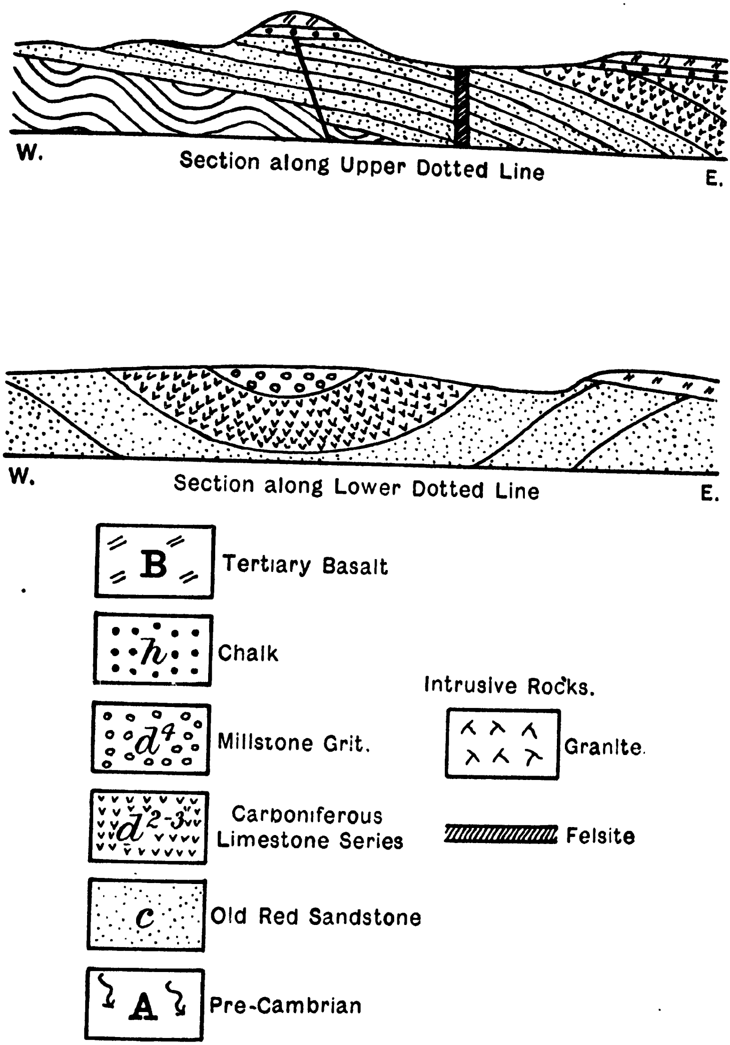


Fig. 75.

Scale 1 inch to the mile.

Cambrian rocks, which throws off a dyke of Felsite towards the north-east.

The Faults.

There are two faults in the area, both of which are post-Carboniferous and pre-Cretaceous. The fault marked F1 has a downthrow towards the south-east, and F2 towards the north-east.

Age of the Igneous Rocks.

The Granite is intrusive in the pre-Cambrian, and its apophysis, the Felsite dyke, cuts the Carboniferous Limestone series. From this we may conclude that the igneous rocks are of post-Carboniferous origin. The dyke is, however, cut and displaced by the fault F2, which is pre-Cretaceous, and thus the age of the intrusions is fixed as between the Carboniferous and Cretaceous periods.

The Basalts rest unconformably upon the chalk, and are stated to be of Tertiary age.

Figures 76 and 77.

(1) *Order of Superposition of Beds.*

From the direction of the dip arrows it is obvious that the stratum marked *a*, occurring in the core of the denuded anticline in the north-west portion of the map, and also cropping out from beneath *b* in the south-east corner, is the oldest rock in the area. It is succeeded conformably by *b*, *c*, and *d*. The rock *e* rests unconformably upon the older series represented by *a*, *b*, and *c*, and is conformably covered by *f*.

(2) *Faults and Folds.*

The rocks of the older series (*a*, *b*, *c*, *d*) are folded along an axis running from north-east to south-west, and are cut by a strike-fault (F1), which throws to the south-east. It narrows the outcrop of *c*, and completely conceals that of *b*. There are also two parallel dip-faults, F2 and F3, which throw towards the north-north-east and south-south-west respectively.

(3) *Igneous Rocks.*

The older series is cut by two dykes, one of Basalt and the other of Lamprophyre.

(4) *Geological History.*

The rocks *a*, *b*, *c*, and *d* were first deposited in the order named. They were then folded along a north-east and south-west axis, the folds being broken through by the fault F1, which, as it runs accurately along the strike of the beds, was probably contemporaneous with the folding.

Then followed the intrusion of the Basalt dyke B, which cuts the fault F1, and is therefore subsequent to it.

Next the faulting along F2 and F3 took place, this being obviously subsequent to the intrusion of the Basalt dyke, which is cut and displaced by them.

The faulting was followed by prolonged denudation of the folded area, after which the strata *e* and *f* were laid down upon the denuded surface of the older beds.

Slight earth movements succeeded the formation of these rocks, imparting to them a low westerly dip.

With regard to the age of the Lamprophyre dyke (L), nothing can be said except that it is newer than the Basalt dyke, and also subsequent to the fault F3, but whether it preceded the deposition of *e* and *f* cannot be determined, as it does not come into contact with those rocks within the limits of the map.

The final act was the removal by denudation of the beds *e* and *f* from the greater part of the area, and the production of the existing topography.

Physical Geography.

The principal hills lie to the north-west of the map, in the region occupied by the rocks *e* and *f*, which form an escarpment.

The axis of the syncline also forms high ground, being the watershed between the two rivers.

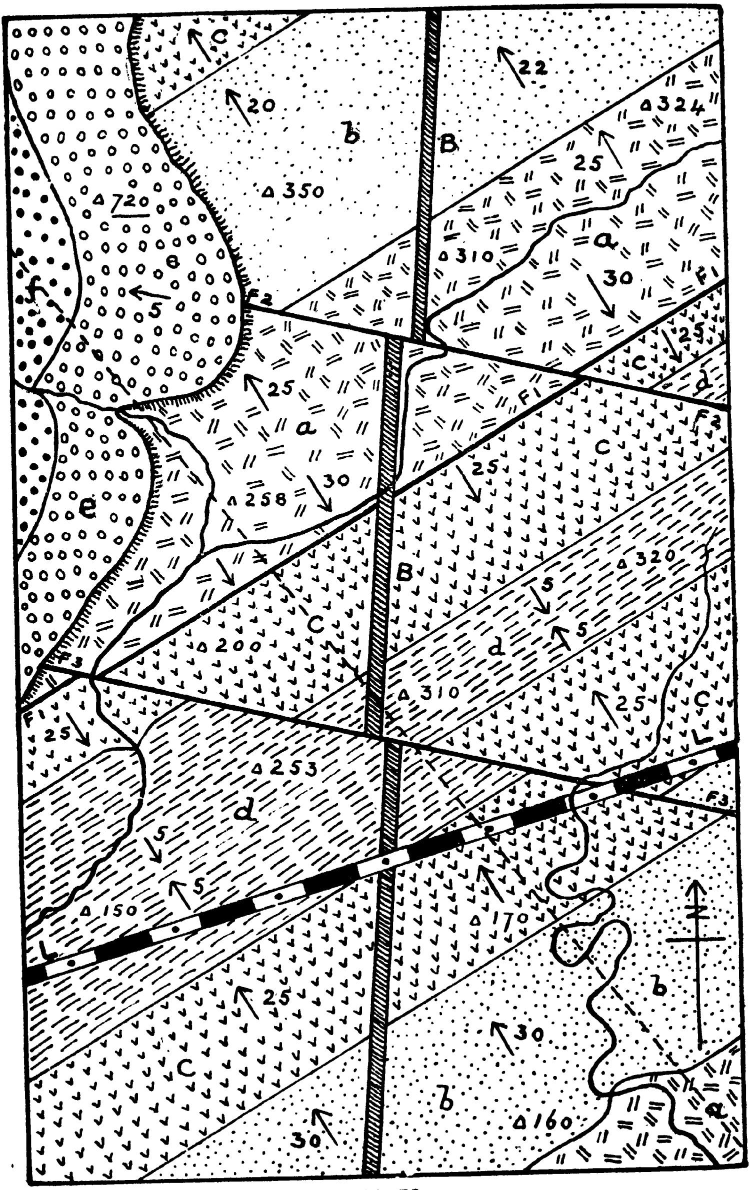


FIG. 76.

Scale 1 inch to the mile.

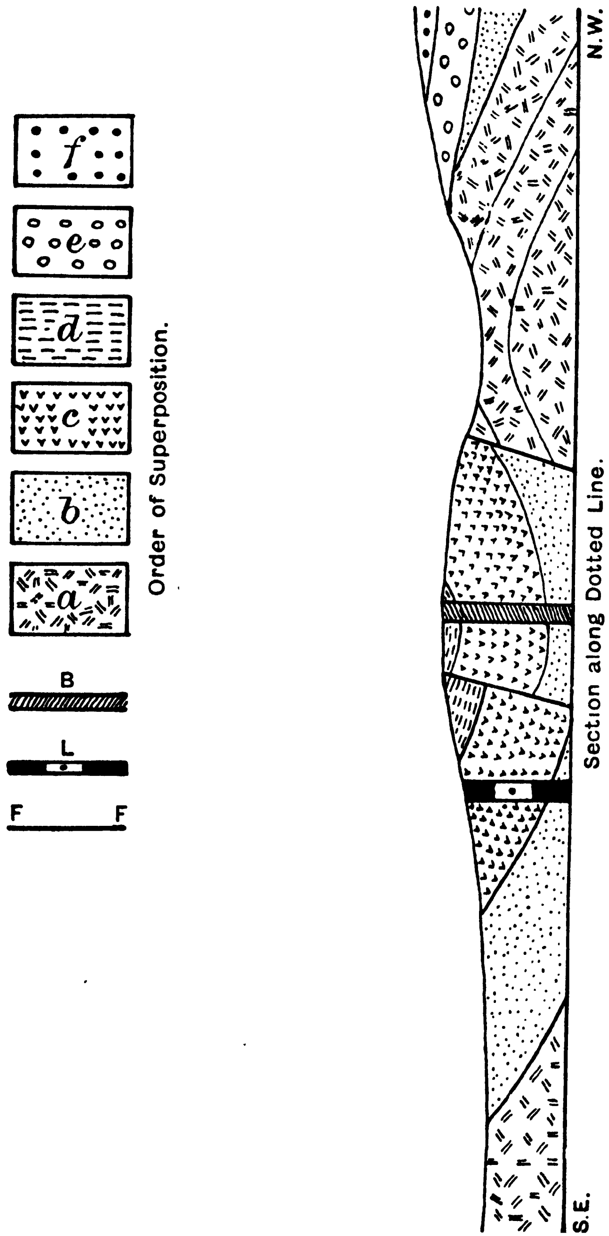


FIG. 77.

Scale 1 inch to the mile.

The larger of the two rivers flows in a valley, excavated on the crest of the anticline, until it reaches the intersection of the fault F2 with the Basalt dyke. Here it is deflected by the igneous rock, and, subsequently, by the fault. It then swings back against the dyke and follows this until it reaches the strike-fault, where it breaks through the dyke and follows F1 to its intersection with F3.

In this section of its course it receives a large tributary (an obsequent stream) from the escarpment to the west. Near the junction of F1 and F3 the river breaks through both faults, cuts through the bed *c*, and flows on to the synclinal area.

The smaller stream rises on the synclinal area and flows in a southerly direction. It is deflected, however, by the Lamprophyre dyke, which it breaks through near its intersection with the fault F3. It then flows on to the approximately level ground in the south-east corner of the map, and in this part of its course develops windings of considerable magnitude.

CHAPTER VIII

GEOMETRICAL SOLUTIONS OF SOME PROBLEMS RELATING TO DIPS

IN the present chapter certain geometrical or graphic constructions of general use in the solution of problems relating to the variation of apparent dip due to change in the direction of the section, depth at which beds of rock may be encountered, and the like, will be described, as they are frequently of practical use in map-reading.

In examining a section in the field it must be remembered that the apparent dip of the strata is not necessarily their true dip, as the section may not be at right angles to the strike. If, however, two sections running in different directions can be found, and the amount of apparent dip and the direction of each be observed, the amount and direction of true dip can be readily determined by one of the following methods:—

I. *Calculation of Dip by Formula.*

(*a*) Where two observed dips (a and β) and the horizontal angle between their directions (μ) are known, required the direction and amount of true dip (δ).

It is first necessary to find the *direction* of true dip, which may be obtained from the following formula, in which θ is the angle between the direction of the dip a and that of true dip:—

$$\tan \theta = \operatorname{cosec} \mu \ (\cot a \tan \beta - \cos \mu).$$

The amount of true dip can then be obtained as follows:—

$$\tan \delta = \tan a \sec \theta.$$

In cases where μ, the angle between the two observed dips, is 90°, as in a rectangular quarry, the matter is much simpler, as in that case

$$\tan^2 \delta = \tan^2 a + \tan^2 \beta.$$

(*b*) Where the direction and amount of true dip are given, the apparent dip in another direction may be obtained from

$$\tan a = \tan \delta \cos \theta$$

where a is the apparent dip required, δ the true dip, and θ the angle between the two directions.

The value of $\cos \theta$ may be readily obtained by means of the slide rule, using the Sine Scale ($\cos \theta = \sin (90° - \theta)$).

It is from the above formula that the values in the table on p. 128 are calculated.

II. *Graphical Methods.*

(*a*) Given the direction and amount of two observed dips, to find the direction and amount of true dip.

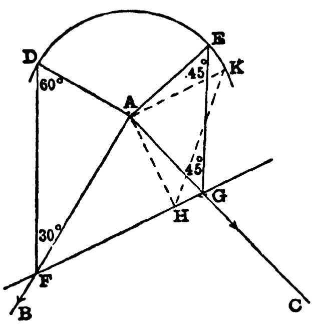


Fig. 78.

Let AB and AC (Fig. 78) be the directions of the two observed dips, and let their amounts be, for example, 30° and 45° respectively.

Draw AD at right angles to AB, making AD of any convenient length (say two or three inches).

Draw AE at right angles to AC, making AE equal to AD.

From D draw DF, cutting AB in F, and making the angle ADF equal to the complement of the angle of dip along AB (90° − 30° = 60°).

The angle AFD will then be 30°, and equal to the dip along AB.

Similarly, make the angle AEG equal to the complement of the dip along AC (*i.e.* 90° − 45° = 45°).

Join FG. This will be the direction of strike.

From A draw AH perpendicular to FG, and meeting it (produced if necessary) in H.

AH, being at right angles to the strike, will be the direction of true dip.

Draw AK at right angles to AH, making AK equal to AD, and join HK.

The angle AHK will be the angle of true dip, and may be measured with a protractor.

Should any difficulty be found in following the above construction, the matter will be made clear if the diagram is carefully drawn upon a piece of thin card, which is then cut through along the lines AD, DF, AE, EG, AK, and KH, and then bent at right angles along AF, AG, and AH. The three lines AD, AE, and AK will then coincide, as will also the points D, E, and K.

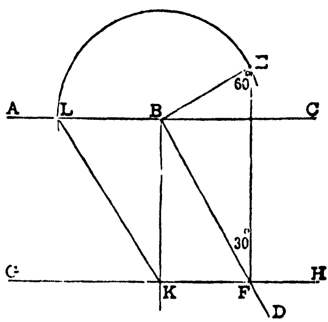


FIG. 79.

DF and EG will now represent the slope of the bed of rock along AB and AC respectively (the two observed dips), and a sheet of card laid across these so that its lower edge lies along FG will represent the bed of rock, and will be found to be also in contact with KH. KH will be found to be the steepest dip on the plane, and therefore the true dip.

(*b*) Given the direction of strike and one observed dip, to find the direction and amount of true dip (Fig 79).

Let ABC be the direction of strike, and BD the direction of the observed dip, which is, say, 30°.

Draw BE of convenient length at right angles to BD, and at E make an angle BEF equal to the

complement of the angle of the observed dip ($90° - 30° = 60°$).

Through F draw GFH parallel to ABC, and from B draw BK at right angles to AB.

The line BK, being at right angles to the strike, will of course be the direction of true dip.

Upon BA mark off BL, equal to BE and join LK. The angle BKL will be the angle of dip.

(*c*) Given the amount and direction of true dip, to find the amount of dip in another given direction.

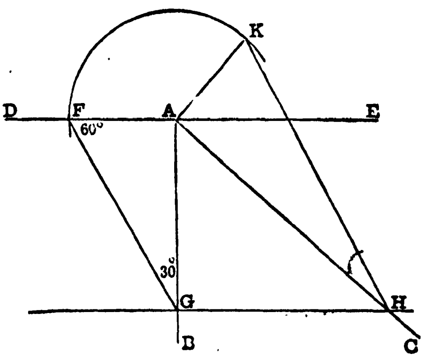


FIG. 80.

Let AB (Fig. 80) be the direction of true dip and its amount 30°, required to find the amount of dip in the direction AC.

Through A draw DAE at right angles to AB. This will be the direction of strike.

On AD mark off AF of any convenient length, and make the angle AFG equal to the complement of the angle of the ~~apparent~~ dip (in this case 60°). true

Through G draw a line parallel to DE, cutting AC in H.

Draw AK at right angles to AC and equal to AF, and join HK. The angle AHK will be the required dip.

(*d*) Given the direction and amount of true dip, to find the direction in which the dip will be of a given amount (of course less than true dip).

Let AB (Fig. 81) be the direction of dip, and let its amount be 30°. Required the direction in which the dip will be 20°.

Through A draw the strike line DAC, and mark off AE of convenient length.

At E make the angle AEF equal to the complement of the angle of dip (90° - 30° = 60°).

Through F draw a line GFH parallel to DAC, and produce BA to K, making AK equal to AE.

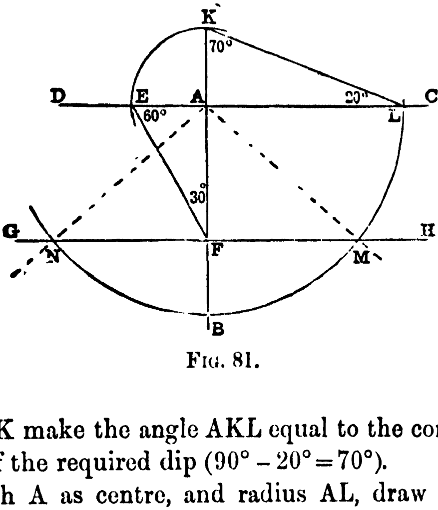


FIG. 81.

At K make the angle AKL equal to the complement of the required dip (90° - 20° = 70°).

With A as centre, and radius AL, draw an arc of a circle cutting GH in M and N.

Join AM and AN. AM and AN will be the required directions, in which the dip will be 20°.

(*e*) Given the depth at which a stratum, say a seam of coal, is encountered in three boreholes, which are not in a straight line, and whose position and height above the sea are known, to determine the dip and strike, and also the depth at which the bed

may be reached at some other place in the neighbourhood.

Let A, B, and C (Fig. 82) be the positions of the three existing boreholes, regarding which the following

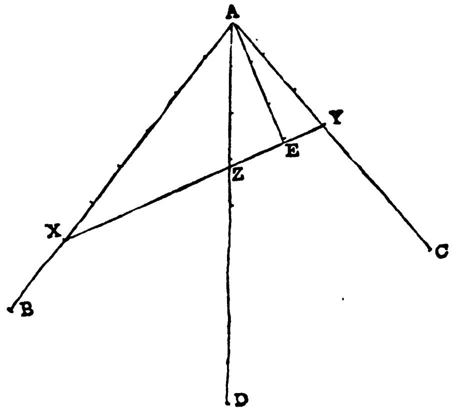


FIG. 82

particulars are known, and D the position of the proposed boring :—

Boring A.

Height above the sea . . .	550 feet.
Depth of seam	2650 „

Boring B.

Height above the sea . . .	725 feet.
Depth of seam	4225 „

Boring C.

Height above the sea . . .	450 feet.
Depth of seam	4450 „

Site D.

Height above the sea . .	220 feet

Distance AB, 8,400 feet.
„ AC, 5,700 „
„ AD, 12,450 „

In order to obtain the gradient of the seam along the lines AB and AC, it will first be necessary to reduce the depths to a common datum. For this purpose sea-level will be convenient in the present case, but any other datum might be chosen.

The depths of the seam below sea-level at A, B, and C are obviously 2100, 3500, and 4000 feet respectively.

The fall of the seam between A and B is 3500 − 2100 = 1400 feet, and the distance from A to B is 8400 feet. The gradient is therefore 1400/8400 or one in six.

Similarly, the gradient along AC is 1900/5700 or one in three.

Mark off from A, along AB, six equal units of convenient length, finishing at X, and three units of the same length along AC, finishing at Y.

Join XY by a line cutting AD at Z.

The seam will be at the same level at X and Y, and therefore the line XY is the direction of strike of the seam.

Ascertain the number of units in AZ (in this case 3·16). This will give the gradient along AD, namely, 1 in 3·16.

The distance from A to D being 12,450 feet, the total fall of the seam will be 12,450/3·16 = 3939·8, say 3940 feet.

The depth below datum at D is therefore 2100 + 3940 = 6040 feet, and since D is 220 feet above the sea, the depth of the seam will be 6040 + 220 = 6260 feet from the surface of the ground.

It will be obvious that the direction and amount of dip may be obtained by a similar method. Draw AE at right angles to XY (the strike). Then AE is the direction of dip, and the number of units in AE will give the gradient along that line, viz. 1 in 2·93, and 2·93 = cot 18° 50′, which is therefore the angle of dip.

(*f*) To obtain the dip and strike of a rock from its outcrop on a contoured geological map

In Fig. 83 the continuous lines are contours, and the broken line represents the outcrop of the bed of rock whose dip and strike are required. A, B, and C are points on the outcrop, and since A and B are on the same level (200 feet), the line AB will be the strike, and AD, at right angles to this, the direction of dip.

At the point C the surface of the bed is 100 feet

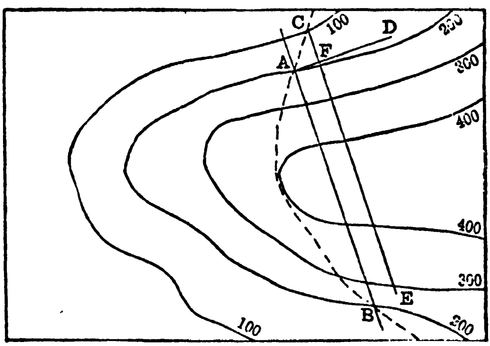


FIG. 83.

above the sea, and the same is true of all points along the line CE, drawn parallel to AB.

The fall of the bed along AF is therefore 100 feet, and the length of AF (say x) can be obtained from the map.

The gradient of the bed is therefore 100 in x, and if θ be the angle of dip, then $\frac{x}{100} = \cot \theta$, from which the value of θ can be obtained.

An extremely useful and at the same time simple method of solving dip problems has been described by Mr. A. Harker,[1] and a selection from his solutions is given below.

[1] "Graphical Methods in Field Geology," *Geological Magazine,* New Series, Decade III., vol. i., 1884, pp. 154–162.

Space does not permit of the introduction of the mathematical proofs of the various constructions employed, and for these the reader is referred to the original article.

The usefulness of the method depends upon the possession of some convenient method of laying down on a diagram a length proportional to the tangent of any given angle, and Mr. Harker describes a protractor which may be used for this purpose, and which also serves as a rough table of tangents and cotangents.

The protractor is of the ordinary oblong form, graduated along a straight edge, the figures increasing both ways from zero at the middle point Z (Fig. 84).

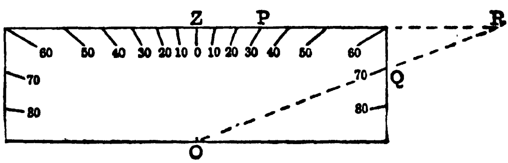


FIG. 84.

If the breadth of the protractor OZ is taken as unity, then the distance from Z to the mark representing any angle is the tangent of that angle. For example, ZP represents the tangent of 30, and ZR that of 70.

In the constructions which follow, a straight line will be said to represent the dip of any given stratum when it is drawn from a fixed line Z—

(1) In the *direction* of the dip; and

(2) Of length corresponding to the *amount* of the dip—that is, the length given on the edge of the protractor from zero to the proper degree mark (tangent).

Practical Applications.

(i) Given the direction and amount of full dip, to find the apparent dip in any given direction.

In Fig. 85 draw ZA to represent the full dip, ZB in the

other given direction, and AB perpendicular to it; then ZB, the part cut off, represents the apparent dip in magnitude as well as direction, and the amount of apparent dip may be read off by applying the edge of the protractor.

(ii) Given the apparent dip in one direction, and the direction of full dip, to find the amount of the latter.

In Fig. 85 draw ZB to represent the apparent dip, and ZA in the direction of full dip, the perpendicular BA will cut off a length ZA, which will represent the full dip.

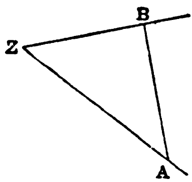


FIG. 85.

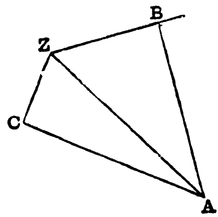


FIG. 86.

(iii) Given the amount of apparent dip in two directions, to find the direction and amount of full dip.

In Fig. 86 draw ZB and ZC to represent the two observed dips, and perpendiculars to them at B and C, meeting in A; then ZA represents the full dip in direction and amount.

A number of other problems which may be solved by similar methods, and which are of considerable importance to the field geologist, is described in the original article.

In the same volume (pp. 412–415) Mr. R. D. Oldham gives two useful diagrams from which the various angles may be read off by inspection.

CHAPTER IX

METHODS OF CONDUCTING A GEOLOGICAL RECONNAISSANCE

IT frequently happens that a young geologist is called upon to take part in a prospecting expedition abroad, and unless he has had some previous training in surveying, which is only too seldom the case, may find himself faced by almost insuperable difficulties when he attempts to reduce the results of his field observations to map form. To such it is hoped the few simple directions which follow may be of use, while those of them dealing with purely geological problems may help engineers and miners who, though familiar with the methods of the surveyor, may have had no previous experience of geological mapping.

The writer has had experience of men who have gone into the field with an outfit of new instruments with the working of which they were entirely unfamiliar. It is true they knew roughly how to take observations with the various pieces of apparatus, but they seemed to be totally ignorant of the degree of accuracy which could be obtained, and the consequent limitations of the several methods. The knowledge of the possible accuracy of a survey can only be obtained by practice with the instruments, and this should be undertaken, whenever time will permit, before starting.

The chiefs of prospecting parties frequently send off their assistants with "sealed orders," and this is no doubt necessary in some cases for commercial purposes, but they would do well to take their geologist into their confidence as regards the exact localities which it is intended to visit. By this means much time may be saved, as it is then possible to obtain such maps as may be published and to

look up the literature of the district or of neighbouring areas, thereby obviating the repetition of work already done by others.

The methods to be employed will of course depend on the existence or non-existence of a topographical map, and in the former case upon the scale, probable accuracy, and amount of detail of the existing survey. Much also will turn upon the size of the area to be inspected, as methods suitable for the close survey of a limited area upon which the party is encamped for some days or weeks are not applicable to a rapid march across country.

Where the country is entirely unmapped and of great extent, positions will have to be determined astronomically by means of a sextant or theodolite, the services of an experienced surveyor will be required, and the description of the methods to be employed do not fall within the scope of the present book.

The existence of a topographical map upon which the salient features of the country are depicted with a reasonable amount of accuracy makes it possible for the geologist, even though not greatly experienced in survey work, to lay down the positions of the main structural features of the area by means of a few simple instruments, the use of which will presently be described. Before starting it is well to prepare enlargements of the portions of existing maps which are to be the subjects of investigation, and these may be used when upon the ground as the basis of the survey, such corrections as may be necessary being made upon the spot.

The instruments which will be found most generally useful are the Prismatic Compass, the Clinometer, and the Plane-table, the first being employed in laying down the general route on extended journeys, and the two last where more detail is required.

The Prismatic Compass.—This instrument consists of a magnetic compass with a moving card on which are

marked the chief points, and whose edge is divided into 360°. It is provided with sights, the one nearest to the eye carrying a total reflection prism, by means of which the graduations on the compass card are rendered visible at the same time as the distant object. The graduations are so arranged that when the observer is looking towards the *magnetic north* the instrument reads 0° or 360°. The other cardinal points read as follows: E. 90°, S. 180°, and W. 270°.

In use the instrument is held in the hands close to the eye, and the sights brought into line with the object whose *bearing* (direction with regard to the magnetic north) it is desired to determine, and the graduation the image of which in the prism coincides with the foresight is recorded.

In order to plot this direction on the map, a line representing the *magnetic meridian* (north and south line obtained by compass) must first be drawn, and then the bearing is laid off by means of a circular protractor, the degrees being read clockwise from the north point.

It will be seen that the simplest operation which can be performed with the aid of the prismatic compass is the determination of the direction and distance of any visible and accessible object. The bearing is obtained and plotted as above described, and the distance measured by tape or chain.

Sketching a Route by Means of the Prismatic Compass.—Where great speed is not essential it will be found desirable to actually draw the map as one proceeds. In order to do this, the observer must be provided with a sketching pad made up of squared paper divided into, say, inches and tenths.

The sketch will be so arranged that the two sets of lines on the paper run north and south and east and west respectively.

On starting from the base a reading will be taken with the compass directed to the most convenient distant object along the forward route, and the direction of this at

this is undesirable, as it is then impossible to verify doubtful observations.

A specimen page of a field-book is given below, and the plan plotted from this forms Fig. 87.

SPECIMEN PAGE OF FIELD-BOOK.

		Camp		
	4.15	14	$2\frac{1}{3}$	
	1.10	87	$2\frac{1}{3}$	Hill 20°—10 miles.
	6.30	360	$2\frac{3}{4}$	
		Camp		
Spring 70 yards	4.20	340	$2\frac{1}{2}$	Stream 10 yards wide with ford 45°.
	1.0	310	$2\frac{1}{2}$	
	4.10	23	2	
		Village of Victoria.		
	Times (Hours and Minutes).	Bearings.	Rates in Miles per Hour.	

In addition to the field-book it is of course important to make notes of the chief geological features encountered, together with the *general* dip of the strata and their character and fossil contents; but it must be borne in mind that detailed work cannot be attempted on a reconnaissance of this kind.

The prismatic compass may also be used for rough surveys of specific areas; but for this purpose the writer prefers the plane-table, the use of which will next be described. The reader will be able to adapt the methods used in the case of the plane-table to surveys with the prismatic compass, as the underlying principle is the same. The chief disadvantages of the plane-table are that it cannot be used in wet weather, and that it is not so readily portable as the prismatic compass.

The Plane-table.—The plane-table consists of a small flat table mounted upon a tripod similar to those in use for photographic cameras, but of somewhat heavier make.

A convenient size of table for general use is 18 inches square. It is provided with a bevelled ruler furnished with a sight at either end, and so adjusted that the line joining the sights is accurately parallel to the edge of the ruler. The ruler should also be graduated with the scale on which it is intended to work.

The sheet of paper upon which the plan is to be drawn is securely fastened to the table by means of drawing-pins.

The trough compass should now be placed upon the table, and a north and south line drawn upon the paper. If now the observer's position be marked upon the sheet by means of a dot or pin-prick, and the ruler be placed against this and then turned (the table, of course, being kept stationary) so that the sights are in line with a distant object, a line (or *ray* as it is called) drawn along the edge of the ruler will represent the direction of the object. In this way a number of *rays* may be drawn to prominent objects all round the observer's position.

Survey by Means of the Plane-table.—It is first necessary to select a site for a base-line, which should be measured as accurately as possible. The site should be so chosen that both ends of the line command good views of the country to be surveyed, and should so far as is possible be approximately level.

The length of the base-line must of course depend upon local circumstance, but the longer the better. From half a mile to a mile is a usual distance.

Having marked the ends of the base-line upon the ground, it must now be drawn to scale upon the paper, and here judgment must be used as to the portion of the paper selected. Thus if the base-line is near the middle of the area to be surveyed, it must be drawn in the centre of the sheet, if say at the southern end of the area, then near the bottom of the sheet, and so forth.

To Fix Points by Intersection.—Set and level the plane-table at one end of the base-line, and by means of the sighted ruler draw rays to the other end of the base, and to any conspicuous objects in the landscape. The names of the objects and, if necessary, a small sketch for purposes of identification should be entered against their number in the field note-book (or upon the plan itself), and their elevation or depression with regard to the observer then measured by means of the clinometer. These should be recorded alongside the rays upon the plan thus (1° E.), (3° D.), &c.

At this stage the magnetic north should be carefully marked upon the plan by means of the trough compass, and it may be used for *checking* the orientation of the table when removed to other points.

Next remove the table to the other end of the base, and proceed as follows:—

1. Orient the table. To do this the ruler is laid along the line representing the base-line upon the sketch, and the table is then turned until the sights are in line with the opposite end of the base, and then clamped. The table is then in the correct position.
2. Draw rays to the distant objects, and again record their elevation or depression.

   The intersection of these rays with those previously drawn to the same objects from the other end of the base will fix the positions of the objects on the plan.
3. Calculate the heights of the objects by means of their distances on the plan and their observed angles of elevation or depression.

These heights should be immediately recorded alongside the points on the plan.

The positions of these main points of the survey having been fixed, they may now be employed to determine the positions of other points in the area by the method of resection.

Resection.—This is the process employed for filling in the detail of the plan. Thus, suppose it is desired to fix the position of some point of particular geological interest which is not visible from the base-line, or only discovered after the observer has left the base.

Set up the plane-table at the point and orient it as accurately as possible by means of the trough compass, and draw *back-rays* from two or three of the main points already fixed, which must of course be visible. It is always preferable to use three points where these are available, and in this case the procedure is as follows:—

Fix the ruler against one of the main points and turn it until the sights are in line, then draw a ray from the main point towards the observer. Repeat this with the two other main points. If the three back-rays intersect in a single point, this is the observer's position. If not, the three rays will form a small triangle, the *triangle of error*, and the following are the rules for the determination of the true position:—

I. If the *triangle of error* is inside the triangle formed by joining the three main points, the observer's position is inside the triangle of error; if outside, outside.

II. In the latter case the observer's position will be either to the right or left of all the rays when facing the three main points. It will be obvious that only two of the six sectors produced by the rays fulfil this condition.

III. The distances of the observer's position from the respective rays is proportional to the lengths of the rays. On the plan, therefore, the position will be nearest to that side of the triangle formed by the shortest ray and furthest from that formed by the longest, and this is true irrespective of whether the position be inside or outside the triangle of error.

In Fig. 88 the triangle of error falls outside the triangle

formed by the three distant stations, and therefore under Rule I. the observer's position is outside the triangle of error. The only sectors which fulfil the conditions of Rule II. are those marked *x* and *y*. Since the point is furthest from the longest ray it must lie in *y*, and its position will be finally determined by Rule III.

In order to check the position thus established, join it by a line with the most distant of the main points, place the ruler along this line, and turn the *table* until the sights are in line with the distant object, then, having clamped the table, test the correctness by means of the other two points.

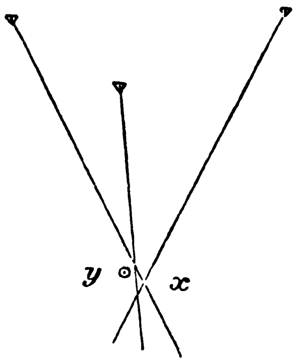


FIG. 88.—Triangle of Error.

Should there still be a triangle of error, it will be necessary to repeat the process.

Resection from Two Points.—This should only be undertaken when a third point cannot be used. The method is similar to that employed for three points, but obviously the single point of intersection of the back-rays must be taken as the observer's position, and its accuracy will be entirely dependent upon that of the compass, and should this latter be affected by local conditions, such as the presence of iron or of magnetic rocks, the position may be entirely unreliable.

Sketching of Detail.—As the survey proceeds, the local detail around each point, whether "main" or "resected," will be sketched in by eye or by pacing or measurement, and the plan thus completed.

Where there is an existing map the matter is of course much simplified, it being only necessary to fill in such detail as may be required either by resection or eye sketching. Where great accuracy is not required the

resection may be carried out by means of a prismatic compass, and the use of the plane-table thus entirely dispensed with where there is an existing map.

In all cases where the amount of the magnetic declination is known, the true geographic north should be indicated upon the map, and when the declination cannot be obtained the word "magnetic" should be inserted, together with the date, *month and year*, so that the necessary correction may be made later.

A useful instrument where detailed information as to the elevations of numerous points is required is the surveying aneroid, which in its most complete form reads to one foot of altitude, but the limitations of such an instrument, affected as it is by changes in atmospheric pressure, must not be forgotten. It should never be used for the measurement of small differences of level except in the most settled weather, and in all cases it is wise to be provided with a self-recording aneroid (barograph), which should be left at the base and used to correct the field observations, the times of which should in this case be recorded.

Having now considered the preparation of the topographical map, we may turn our attention to the geological structure. It is impossible here to enter fully into all the details of geological surveying, involving as it does the whole subject of field geology, but a few general principles and hints as regards the collection of data and specimens may not be out of place.

In the first place, an attempt should be made to locate the main structural lines of the district during the progress of the topographic survey. These should include the axes of the main folds, the direction of faults and dykes of igneous rock, main escarpments, and the position of good sections which it is thought will repay detailed study, and of old workings and the like.

Next, if the formation or formations present in the country are not already known, it is desirable to ascertain them, which may usually be done by means of the fossils.

In the absence of fossils the geologist will be more than ever dependent upon the accuracy of his map, as he will have to work entirely upon stratigraphical and lithological lines.

The best sections of a country are usually to be found along the courses of streams or in sea cliffs, and these should be first visited; the direction of strike and the amount of the dip being recorded, a sketch of the section should be made in the note-book, and specimens should be collected.

Each locality where observations are made should be marked on the map by a number which should correspond with that in the note-book, and should also be painted upon all specimens collected. For this purpose a good varnish for home use is made by dissolving ordinary red sealing-wax in methylated spirits, but as this dries up rapidly in hot climates, one of the enamel paints upon the market may be substituted. This should be purchased in the smallest tins available, as it is much better to take a number of small tins than one large one. The specimens should be wrapped separately in paper, and stored in small canvas bags taken for the purpose.

It often happens that a stream course is so encumbered by boulders that the solid rock is obscured over considerable distances, and attention must then be turned to the boulders themselves, it being remembered that as the material is travelling down stream, boulders will not occur above the outcrop of the parent rock or vein, except in the case of a glaciated region where materials are frequently carried uphill.

Having established the sequence of the beds in one stream course, the attempt must be made to identify the various strata in a neighbouring valley, and when this has been done the corresponding outcrops may be linked up on the map either by eye-sketching or by the methods described in Chapter III., if the map be contoured.

It will first be necessary to map the areas occupied by the various formations, and in doing this the dip of the

strata should be inserted wherever it is possible to observe it with accuracy. This having been done, minor details such as the outcrops of beds of economic importance, *e.g.* coal or ironstone, may be added, together with the position of such mineral veins, faults, and fissures as may have been discovered.

The possibilities of the country as regards water-supply, both potable and for manufacturing purposes, must also receive attention, and this not only as regards surface waters, but also the probability of obtaining a supply from underground.

Where the rocks are not actually exposed at the surface, the soil, if not too thick, will often yield information with regard to their nature, and since the soil and subsoil tend to travel down hill, the boundaries may be determined approximately by the failure of pebbles of the lower rocks, as soon as their concealed outcrops have been passed.

Lines of springs upon a hillside often mark the outcrop of an impervious stratum, and in some instances a change in the character of the vegetation may also give valuable information.

The configuration of the ground will frequently show the position of an outcrop, particularly in the case of a hard rock resting upon softer material, when a more or less distinct step will be observed.

The manner in which concealed outcrops may be plotted upon contoured maps has already received attention in Chapter III., and the way in which they may be approximately mapped by eye-sketching is indicated in Figs. 89 and 90, of which the former is a rough map of the features actually observed in the field, and the latter the finished plan.

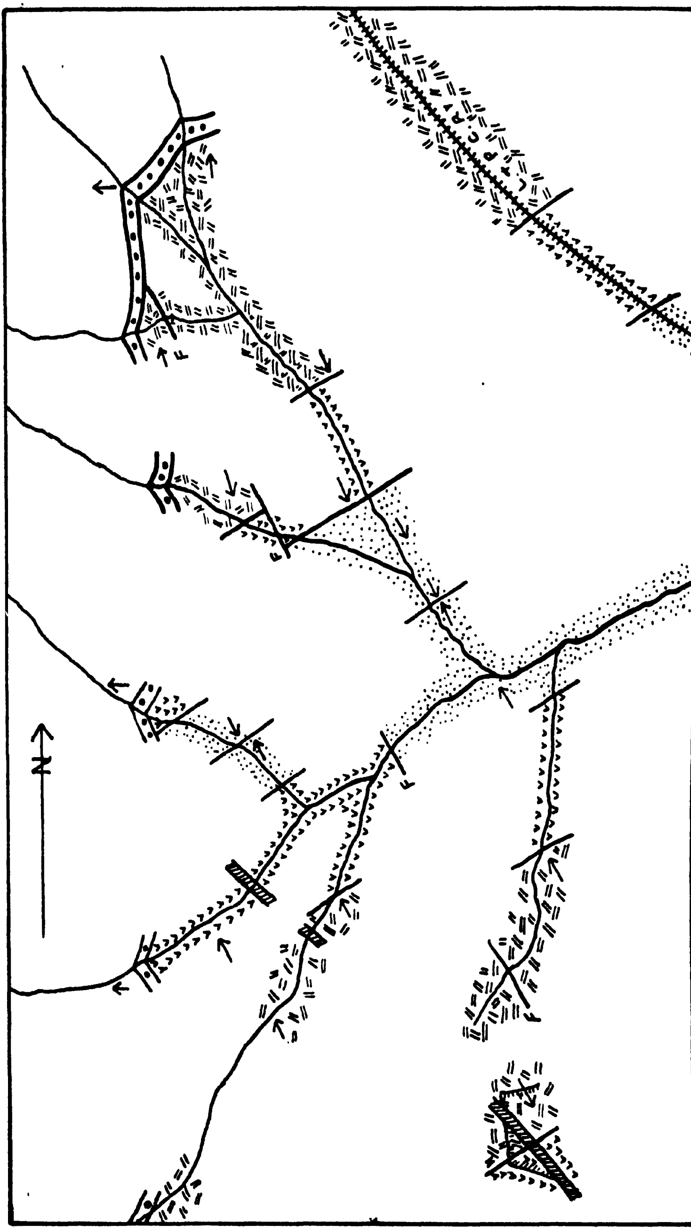


FIG. 89.

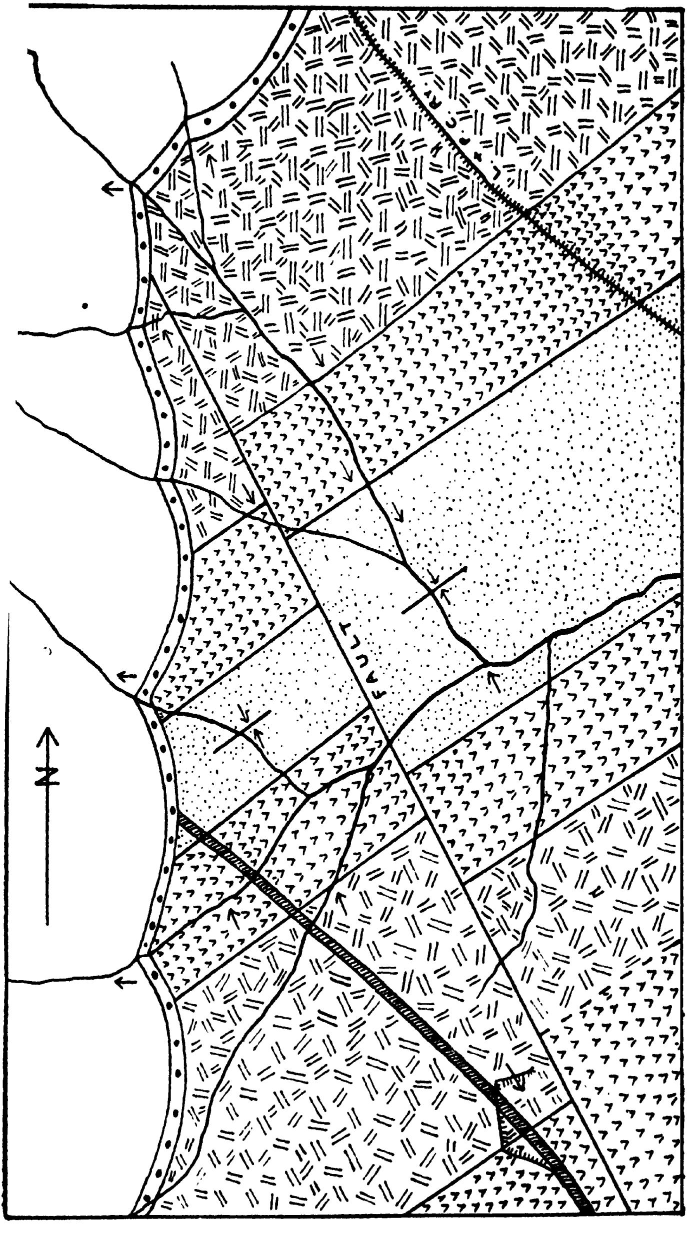


FIG. 90.

Appendix I.—Table to Show Variation of Dip with Change of Direction.

Angle between Direction of Dip and of Section.	Angle of Full Dip.							
0°	10°	15°	20°	25°	30°	35°	40°	45°
10° . . .	9° 51′	14° 47′	19° 43′	24° 48′	29° 37′	31° 37′	39° 31′	41° 34′
15° . . .	9° 40′	14° 31′	19° 23′	24° 15′	29° 9′	34° 4′	39° 2′	44° 1′
20° . . .	9° 24′	14° 8′	18° 53′	23° 39	28° 29′	33° 21′	38° 15′	43° 13′
25° . . .	9° 5′	13° 39′	18° 15′	22° 55′	27 37′	32° 21′	37° 15′	42° 11′
30° . . .	8° 41′	13° 34′	17° 30′	22° 0′	26° 34′	31° 13′	36° 0′	10° 54′
35° . . .	8° 13′	12° 28′	16° 36′	20° 54′	25° 18′	29° 50′	34° 39′	39° 19′
40° . . .	7° 41′	11° 36′	15° 35′	19° 39′	23° 51′	28° 12′	32° 41′	37° 27′
45° . . .	7° 6′	10° 4′	14° 25′	18° 15′	22° 12′	26° 29′	30° 41′	35° 16′
50° . . .	6° 28′	9° 46′	13° 10′	16° 41′	20° 21′	24° 14′	28° 25′	32° 41′
55° . . .	5° 46′	8° 44′	11° 48′	14° 58′	18° 19′	21° 53′	25° 42′	29° 50′
60° . . .	5° 2′	7° 38′	10° 19′	13° 7′	16° 6′	19° 18′	22° 45′	26° 33′
65° . . .	4° 15′	6° 28′	8° 45′	11° 9′	13° 43′	16° 29′	19° 31′	22° 55′
70° . . .	3° 27′	5° 14°	7° 6′	9° 3′	11° 10′	13° 28′	16° 0′	18° 53′
75° . . .	2° 37′	3° 33′	5° 23′	6° 53′	8° 30′	10° 16′	12° 15′	14° 30′
80° . . .	1° 45′	2° 40′	3° 37′	4° 37′	5° 44′	6° 56′	8° 17′	9° 51′
85° . . .	0° 53′	1° 20′	1° 49′	2° 20′	2° 53′	3° 30′	4° 11′	4° 59′
89° . . .	0° 10′	0° 16′	0° 22′	0° 28′	0° 35′	0° 42′	0° 50′	1° 0′

0°	50°	55°	60°	65°	70°	75°	80°	85°	89°
10° . . .	49° 34′	54° 35′	59° 37′	64° 40′	69° 43′	74° 47′	79° 51′	84° 56′	88° 59′
15° . . .	49° 1′	54° 4′	59° 8′	64° 14′	69° 21′	74° 30′	79° 39′	84° 50′	88° 58′
20° . . .	48° 14′	53° 19′	58° 26′	63° 36′	68° 49′	74° 5′	79° 22′	84° 41′	88° 56′
25° . . .	47° 12′	52° 18′	57° 30′	62° 46′	68° 7′	73° 32′	78° 59′	84° 29′	88° 54′
30° . . .	45° 51′	51° 3′	56° 19′	61° 42′	67° 12′	72° 48′	78° 29′	84° 11′	88° 51′
35° . . .	44° 17′	49° 29′	54° 49′	60° 21′	66° 8′	71° 53′	77° 51′	83° 54′	88° 47′
40° . . .	42° 23′	47° 35′	53° 0′	58° 40′	64° 35′	70° 43′	77° 2′	83° 29′	88° 42′
45° . . .	40° 7′	45° 17′	50° 46′	56° 36′	62° 46′	69° 11′	76° 0′	82° 57′	88° 35′
50° . . .	37° 27′	42° 33′	48° 4′	54° 2′	60° 29′	67° 22′	74° 40′	82° 15′	88° 27′
55° . . .	34° 21′	39° 26′	44° 47′	50° 53′	57° 36′	64° 58′	72° 75′	81° 20′	88° 15′
60° . . .	30° 47′	35° 32′	40° 54′	46° 59′	53° 57′	61° 49′	70° 34′	80° 5′	88° 0′
65° . . .	26° 44′	31° 7′	36° 14′	42° 11′	49° 16′	57° 37′	67° 21′	78° 19′	87° 38′
70° . . .	2[illegible]° 11′	26° 2′	30° 29′	36° 15′	43° 13′	51° 55′	62° 43′	75° 39′	87° 5′
75° . . .	17° 9′	20° 17′	24° 8′	29° 2′	35° 25′	44° 1′	55° 41′	71° 20′	86° 9′
80° . . .	11° 41′	13° 55′	16° 44′	20° 25′	25° 30′	32° 57′	41° 33′	63° 15′	84° 15′
85° . . .	5 56′	7° 6′	8° 35′	10° 35′	13° 28′	18° 1′	26° 18′	41° 54′	78° 11′
89° . . .	1° 11′	1° 26′	1° 44′	2° 9′	2° 45′	3° 44′	5° 31′	11° 17′	44° 15′

Appendix II.—Table of Natural Sines, Tangents, and Co-tangents

Angle.	Radians.	Sine.	Tangent.	Co-tangent.	Cosine.		
0°	0	0	0	∞	1	1·5708	90°
1	·0175	·0175	·0175	57·2900	·9998	1·5533	89
2	·0349	·0349	·0349	28·6363	·9994	1·5359	88
3	·0524	·0523	·0524	19·0811	·9986	1·5184	87
4	·0698	·0698	·0699	14·3006	·9976	1·5010	86
5	·0873	·0872	·0875	11·4301	·9962	1·4835	85
6	·1047	·1045	·1051	9·5144	·9945	1·4661	84
7	·1222	·1219	·1228	8·1443	·9925	1·4483	83
8	·1396	·1392	·1405	7·1154	·9903	1·4312	82
9	·1571	·1564	·1584	6·3138	·9877	1·4137	81
10	·1745	·1736	·1763	5·6713	·9848	1·3963	80
11	·1920	·1908	·1944	5·1446	·9816	1·3788	79
12	·2094	·2079	·2126	4·7046	·9781	1·3614	78
13	·2269	·2250	·2309	4·3315	·9744	1·3439	77
14	·2443	·2419	·2493	4·0108	·9703	1·3265	76
15	·2618	·2588	·2679	3·7321	·9659	1·3090	75
16	·2793	·2756	·2867	3·4874	·9613	1·2915	74
17	·2967	·2924	·3057	3·2709	·9563	1·2741	73
18	·3142	·3090	·3249	3·0777	·9511	1·2566	72
19	·3316	·3256	·3443	2·9042	·9455	1·2392	71
20	·3491	·3420	·3640	2·7475	·9397	1·2217	70
21	·3665	·3584	·3839	2·6051	·9336	1·2043	69
22	·3840	·3746	·4040	2·4751	·9272	1·1868	68
23	·4014	·3907	·4245	2·3559	·9205	1·1694	67
24	·4189	·4067	·4452	2·2460	·9135	1·1519	66
25	·4363	·4226	·4663	2·1445	·9063	1·1345	65
26	·4538	·4384	·4877	2·0503	·8988	1·1170	64
27	·4712	·4540	·5095	1·9626	·8910	1·0996	63
28	·4887	·4695	·5317	1·8807	·8830	1·0821	62
29	·5061	·4848	·5543	1·8040	·8746	1·0647	61
30	·5236	·5000	·5774	1·7321	·8660	1·0472	60
31	·5411	·5150	·6009	1·6643	·8572	1·0297	59
32	·5585	·5299	·6249	1·6003	·8480	1·0123	58
33	·5760	·5446	·6494	1·5399	·8387	·9948	57
34	·5934	·5592	·6745	1·4826	·8290	·9774	56
35	·6109	·5736	·7002	1·4281	·8192	·9599	55
36	·6283	·5878	·7265	1·3764	·8090	·9425	54
37	·6458	·6018	·7536	1·3270	·7986	·9250	53
38	·6632	·6157	·7813	1·2799	·7880	·9076	52
39	·6807	·6293	·8098	1·2349	·7771	·8901	51
40	·6981	·6428	·8391	1·1918	·7660	·8727	50
41	·7156	·6561	·8693	1·1504	·7547	·8552	49
42	·7330	·6691	·9004	1·1106	·7431	·8378	48
43	·7505	·6820	·9325	1·0724	·7314	·8203	47
44	·7679	·6947	·9657	1·0355	·7193	·8029	46
45	·7854	·7071	1·0000	1·0000	·7071	·7854	45
		Cosine	Co-tangent	Tangent	Sine	Radians	Angle

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